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Non Road All Terrain Vehicle & Side-by-Side In Service Monitoring based on PEMS

Lessons Learned from the European Pilot Program

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Contents

Abstract

This report summarizes the results of a pilot program dedicated to develop a procedure for the In Service Monitoring of Non Road All Terrain & Side-by-Side vehicles based on Portable Emission Measurement System (PEMS). The tests took place between September 2017 and September 2018.

The reported work addresses the possibility to mount the portable emission measurement system (PEMS) on board of such machinery/vehicle, and the accuracy and precision of measuring regulated exhaust gaseous pollutant emissions using PEMS. It was found that the overall uncertainty of the measurement was within 10%, as compared to a standard test performed in a JRC's chassis dyno test cell (VELA_1).

On road tests showed that the results were stable and reproducible.

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Executive summary

Regulation (EU) 2016/1628, which repeals Directive 97/68/EC, lays down gaseous and particulate emission limits and type approval requirements for internal combustion engines installed in Non-Road Mobile Machinery. This so-called Stage V emission standard includes a wider range of engine types and sizes and it covers previously unregulated engines, including snowmobiles, All Terrain Vehicles (ATV) and engines below 19 kW or over 560 kW. Furthermore the Stage V regulation prescribes for the first time the monitoring of actual in-use emissions of in-service engines installed in non-road mobile machinery and operated over their normal operating duty cycles. It also empowers the Commission "to conduct pilot programmes with a view to developing appropriate test procedures for those engines categories and sub-categories in respect of which such test procedures are not in place"

This report presents the outcome of the pilot programme designed to explore the suitability of the already existing procedure to monitor the gaseous pollutant emissions from variable speed engines in the 56 kW to 560 kW power range (engines of categories NRE-v-5 and NRE-v-6) for its application to test in-service (ISM) internal combustion engines installed in NRMM category ATS (i.e. SI engines exclusively for use in All-terrain and Side-by-Side vehicles). The report confirms that for ISM tests, the use of Portable Emission Measurement Systems (PEMS) is suitable as it can be reliably mounted on the tested machine and the data can also be processed in a similar fashion as in the case for NRMM engines of category NRE-v-5 and NRE-v-6.

Because of the characteristics of ATS NRMM (i.e. this category of engines tend to be single- or 2-cylinders) the measurement of the exhaust mass flow using flow meters (EFM) has turned to be more complicated than expected due to the exhaust flow pulsation typical of this kind of engines. Technical solutions have been found to measure the exhaust flow with an acceptable uncertainty.

During the performance of the pilot programme solutions were also found for the definition of the reference quantities; i.e. work and CO_2 for the case that the type approval test is the NRSC (steady state test cycle) rather than the NRTC (transient test cycle). It has also been proposed a methodology to calculate an equivalent power from the measured CO_2 flow in order to make possible the definition of working and non-working event for the case of mechanically controlled engines (no ECU). The validation of this approach suggests that the approach is suitable for the purpose to define valid/invalid events.

Finally, some recommendations are made in term of test duration (i.e. 3 to 5 times the reference quantity rather than 5 to 7 times) and the use of combined data sampling to satisfy the characteristic of this category of engines in view to amend the present ISM regulation. This is needed to extend the ISM procedures to all the NRMM engine categories as required by the STAGE V legislation.

1 Introduction

The European Commission is committed to improve the EU air quality by, among other instruments, the implementation of emission regulations. The Commission also works on the improvement of testing procedures for pollutant emissions and fuel consumption. This helps to assess the performance of vehicles under real-life conditions.

The European Union legislation on Non-Road Mobile Machinery (NRMM[1]) has been for some time under revision. Regulation (EU) 2016/1628 ([2]), which repeals Directive 97/68/EC[3], lays down gaseous and particulate emission limits and type approval requirements for internal combustion engines installed in such NRMM. This so-called Stage V emission standard includes a wider range of engine types and sizes and it covers previously unregulated engines, including snowmobiles, All Terrain Vehicles (ATV) and engines below 19 kW or over 560 kW. Furthermore the new Stage V NRMM regulation prescribes for the first time the monitoring of actual in-use emissions of in-service engines[4] installed in non-road mobile machinery and operated over their normal operating duty cycles. It also empowers the Commission "to conduct pilot programmes with a view to developing appropriate test procedures for those engines categories and sub-categories in respect of which such test procedures are not in place". In-Service Monitoring procedures prescriptions for engines in the categories NRE-v-5 and NRE-v-6 (variable speed engines with power in the 56 to 560 kW range) are given by Regulation (EU) 2017/655[5] and they are based on the use of Portable Emissions Measurement Systems (PEMS).

DG-GROW[6] has commissioned to the European Commission - Joint Research Centre (EC-JRC) In-service Monitoring (ISM) Pilot Programmes, in the framework of the Administrative Agreement No *SI2.784345 - JRC.35074*, to develop such ISM test procedures

The study reported here investigates whether the ISM provisions already in place for engines in the categories NRE-v-5 and NRE-v-6 are fit to be used in All Terrain Vehicles (ATVs) and Side-by-Side Vehicles (SxS or SbS). Based on the outcome of this Pilot Program that JRC has launched in close collaboration with ATVEA, the Commission will propose a methodology to perform the ISM of NRMM for this category of vehicles.

The main goals of this pilot program phase are:

1. to verify the feasibility in the assembling of such PEMS equipment on these small vehicles,
2. to check for the accuracy of the emission measurements using Portable Emission Measurement System (PEMS) together with the possibility to evaluate the exhaust mass flow rate using an Exhaust Flow Meter (EFM).
3. to define an appropriate testing protocol with the participation of the OEMs

The data evaluation principle used is the so called Moving Averaging Windows (MAW) method based on either the work performed or the CO_2 mass emission at type approval.

1 'Non-Road Mobile Machinery' means any mobile machine, transportable equipment or vehicle with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on roads.

2 REGULATION (EU) 2016/1628 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC. Official Journal L 252/53. Available at: http://eur-lex.europa.eu

3 DIRECTIVE 97/68/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery, Official Journal L 59. Available at: http://eur-lex.europa.eu

4 'In-service engine' means an engine that is operated in non-road mobile machinery over its normal operating patterns, conditions and payloads, and is used to perform the emission monitoring tests.

5 COMMISSION DELEGATED REGULATION (EU) 2017/655 of 19 December 2016 supplementing Regulation (EU) 2016/1628 of the European Parliament and of the Council with regard to monitoring of gaseous pollutant emissions from in-service internal combustion engines installed in non-road mobile machinery. Available at: http://eur-lex.europa.eu

6 Directorate General Internal Market, Industry, Entrepreneurship and SMEs.
http://ec.europa.eu/growth/index_en

2 NRMM PEMS Pilot Program for ATVs

2.1 Objectives

The NRMM PEMS Pilot Program and the relative test campaign were launched to facilitate the understanding of the PEMS application as a tool for ISM.

The objectives of the program were defined as follows:

- To provide a sort of guideline for the installation of PEMS in All Terrain Vehicle and Side-by-Side (including mechanical fittings)
- To validate the use of gaseous PEMS for checking the ISM of engines mounted in ATVs and SxS NRMM/vehicles (NRMM engine category ATS[7])
- To develop a test protocol for the above mentioned vehicles
- To develop and share 'best practise' for the use of gaseous PEMS approach in NRMM ISM testing to all relevant stakeholders

2.2 Scope

This Pilot Programme is dedicated to develop a ISM procedure for NRMM All Terrain and SxS vehicles variable speed spark-ignition engines in order to ensure that the designed procedure (Reg. (EU) 2017/655), which is based on a reduced set of data, is appropriate to limit the exhaust pollutant emissions of engines installed in this category of NRMM over their normal operation.

2.3 Technical Elements

The envisaged technical elements were formulated paying particular attention to:

1. The application of the test protocol, e.g. to judge whether the mandatory data and its quality were appropriate for the final evaluation;

2. The method used to analyse the emissions data i.e. to answer the following question: "Once the data has been collected correctly, what is the most appropriate method to the test data measured with PEMS to judge whether the engine is in conformity with the applicable emissions limits?"

[7] 'category ATS':SI engines exclusively for use in ATVs and SbS; engines for ATVs and SbS other than SI engines are included in the category NRE.

3 Tests description

3.1 Test machines/vehicles

The definition of a strategy for the selection of vehicles was part of the pilot program. The selection process involved vehicles manufacturers and their industrial association (ATVEA).

ATVEA is the **A**ll **T**errain **V**ehicle Industry **E**uropean **A**ssociation. ATVEA is a non-profit industry association founded in 2003, at a moment when the ATV (All Terrain Vehicle) market began to experience strong growth. Since 2010, ATVEA is also working on the correct and responsible use of Side-by-Side vehicles, which represent an increasingly important market in Europe.

The participating manufacturers tested between 1 and 2 vehicles during the test campaign. Some variations might be observed from one vehicle to another.

ATVEA has summarised into two main categories (see Tables 1 and 2), the engine families intended for the purpose of ISM In particular, three-way catalytic converter will become the mainstream emission control technology once NRMM Stage V becomes applicable. However until then, current engines may not be equipped with any emission control system as they were not yet falling into the new NRMM regulation scope.

The vehicle duty cycles had to be representative of the machine type, i.e. the manufacturers had to screen machines/vehicles to ensure testing is conducted within the normal range of applications for that engine/machine type. Particular attention was paid to the PEMS installation constraints.

All the vehicles were used in 4x4 or 6X6 configuration.

Table 1. EU-PEMS ATVS & SxS Pilot program families.

	Engine Family 1	**Engine Family 2**
Engine type	4 strokes	4 strokes
Fuel Type	Petrol	Petrol
Fuel system	Electronic Fuel Injection (EFI)	Electronic Fuel Injection (EFI)
Cooling system	Water-cooled	Water-cooled
Emission control system	None / Three-way catalytic converter	Three-way catalytic converter
Engine displacement range	400-1000cc	700-1000cc
Number of cylinder	1 or 2	1 or 2
Valve type	SOHC	SOHC

Source: OEM, 2017

Table 2. EU-PEMS AVS & SxS Pilot program families (further details).

VEHICLE FAMILY	CODE	MACHINE TYPE	QTY OF CYLINDERS	AFTERTREATMENT
1	A	Quad	1	NONE
1	B	Quad	1	NONE
2	C	SxS	1	TWC
1	D	Quad	1	NONE
2	E	SxS	2	TWC
1	F	Quad (6x6)	2	TWC

3.2 Vehicles details (fleet)

The details of the different vehicles/machines are summarised in Table 3.

Table 3. EU-PEMS AVS & SxS Pilot program (detail of vehicles).

Vehicle	OEM	Type	No. of Cylinder	Displacement [cc]	Stroke	Fuel	Rated Power (MODE_1) [kW]	Aftertreatment	Emission Limits* [g/kWh]		CAN Logger
									NOx+THC	CO	
A	1	ATV	1	420	4	Gasoline	18.30	None	8	400	OEM
B	2	ATV	1	567	4	Gasoline	18.21	None	8	400	Aftermarket (Kvaser)
C	1	SbS	2	675	4	Gasoline	19,28	TWC	8	400	OEM
D	3	ATV	1	475	4	Gasoline	18.23	None	8	400	Aftermarket (Kvaser)
E	3	SbS	1	999	4	Gasoline	50.88	TWC	8	400	Aftermarket (Kvaser)
F	4	ATV	2	976	4	Gasoline	39.6	TWC	8	400	Aftermarket (Kvaser)

Source: OEM, 2017

*See Annex 1 for an overview of the Stage V emission limits by engine category

3.3 Test circuit

A moto-cross field was available to the JRC and therefore selected to perform the ISM tests. This proving ground was found suitable for the type of testing to be performed. Figures 1 to 4 provide a general overview of the test field together with its altimetry.

The characteristic of the surface was sandy; generally soft with grass and sometimes, on certain tests, it became mud-covered due to adverse weather conditions.

Figure 1. Cross field test track and relative altimetry (1 lap).

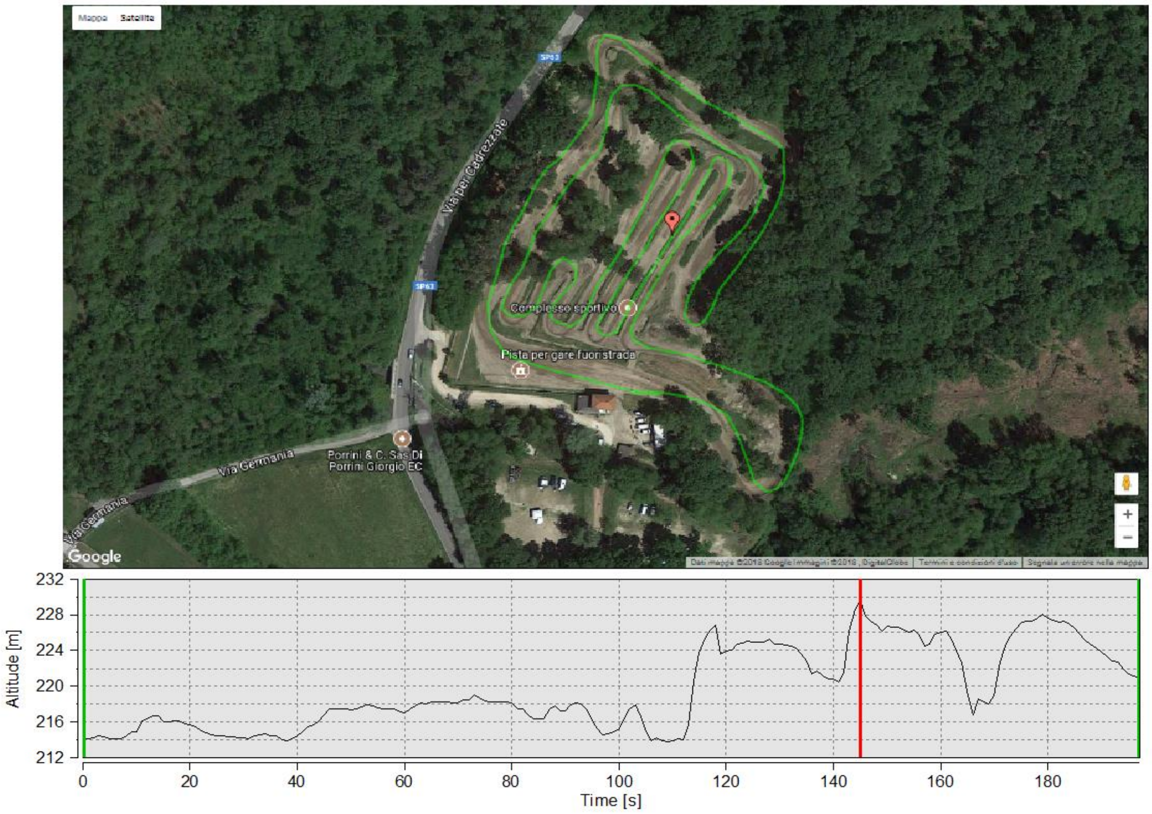


Figure 2. Cross test field overview (1).

Figure 3. Cross test field overview (2).

Figure 4. Cross test field overview (3).

3.4 Test Execution

3.4.1 Test equipment

The PEMS systems used to test the vehicles had to comply with the following general requirements:

1. To be small, lightweight and easy to install;
2. To work with a low power consumption so that tests of at least 1 hour can be run with a single set of batteries;
3. To measure and record the concentrations of NOx, CO, CO_2, THC gases in the vehicle exhaust;
4. To record the relevant parameters (engine data from the ECU –if available–, vehicle position from the GPS, weather data, etc.) on an included data logger.

The EFM systems used to test the vehicles had to comply with the following general requirements:

1. To be small, lightweight and easy to install;
2. The pipe size and diameter should be choose according to the vehicle exhaust flow values (see EFM manufacturer recommendation)
3. To measure and record the Exhaust Mass Emission in kg/h

3.4.2 Test protocol and test condition

The tests were conducted in agreement with the OEMs and following their recommendations developed in the preliminary phases.

The test machines had to run over normal duty cycles, conditions and payloads, defined by the vehicle manufacturers, in consultation with their type approval authorities. According to the draft test protocol[8], the test duration had to be selected to have a cumulative vehicle work produced during the test between 5 to 7 times the work or the CO_2 produced in the certification test cycle (NRSC – G2 Mode)

3.4.3 Test trips and cycles

Each machine was tested according to a duty cycle representative of the category.

For each machine, the following test protocol has been used (see Table 4):

[8] The bases for the test were those defined in Reg. (EU) 2017/655; i.e. ISM procedure for engines NRE-v-5 and NRE-v-6

Table 4. ATV and SBS ISM test cycle.

	CYCLE	TEST STEP SEQUENCE
Day 1		
Morning	Step Test Cycle 1	1-2-3
Morning	Step Test Cycle 2	1-2-3
Afternoon	Step Test Cycle 3	1-2-3
Day 2		
Morning	Random Cycle test	4
Afternoon	Step Test Inverse Cycle	2-1-3
Afternoon	Step Test Inverse Cycle	3-2-1
Day 3		
Morning	Draw weight test	5

Source: JRC.Vela, 2017

Test cycles have been selected according to the indication provided by ATVEA, and adapted to the test track available.

The characteristics of the tests conditions suggested by ATVEA are described in Table 5 while an extra test cycle named random was added by the JRC to obtain an indication of the machine operation without a fixed and defined engine conditions. A further drag test of a real weigh was also added.

Table 5. ATV and SBS ISM test cycle (overview).

Step	Speed (Km/h)	Time (min.)	Traction	Description and notes
1	0-20	15	Low torque	Flat terrain constant speed with acceleration
	Idle	5	-	
2	20-40	20	High torque	Hills, acceleration
	Idle	5	-	
3	40-60	15	Medium torque	Flat terrain constant speed with acceleration
total		60		

Source: JRC.Vela, 2017

Step Test Cycle

It was selected a test cycle to cover all possible operating conditions of the machines under testing.

Step1 is nearly a constant speed run at 20 km/h with acceleration, performed on a flat area with a low engine torque. Panel 1 of Figure 5 depicts the speed vs time operation of this step.

Step2 is a high demanding torque run on a hill terrain. Panel 2 of Figure 5 depicts the speed vs time operation of this step.

Step 3 is almost a constant speed run at 40-60- km/h with acceleration, performed on a flat area with medium engine torque. Panel 3 of Figure 5 depicts the speed vs time operation of this step.

Tests were repeated using different sequences (e.g.: 1-2-3, 2-1-3, 3-2-1) to verify the effect on exhaust emissions of each step in the sequence.

After each running step, 5 minutes of idle speed was introduced to measure exhaust emission also at idle speed but also to make general inspection of the vehicle, like status of instrumentation due to high vibrations, fuel level control and battery replacement if necessary.

The complete test had a total duration of 1 hour. All the exhaust emission and additional vehicle parameters were recorded for later post-processing.

Random Cycle test (Step 4)

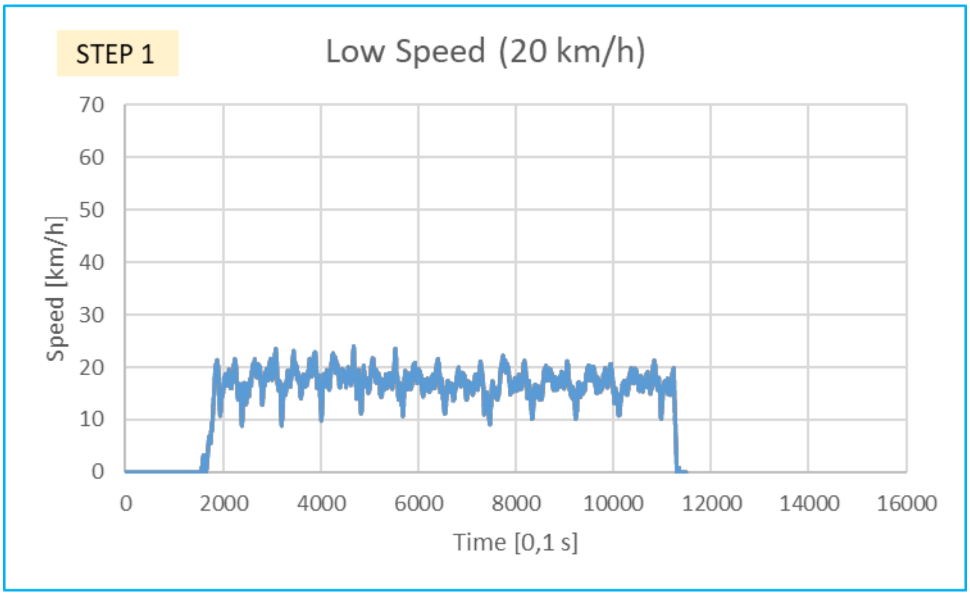
A random cycle test lasting 1-hour was performed on the same test track by running the test machines without carrying the test cycle in any specific steps. Panel 4 of Figure 5 depicts the speed vs time operation of this step.

Draw weight test (Step 5)

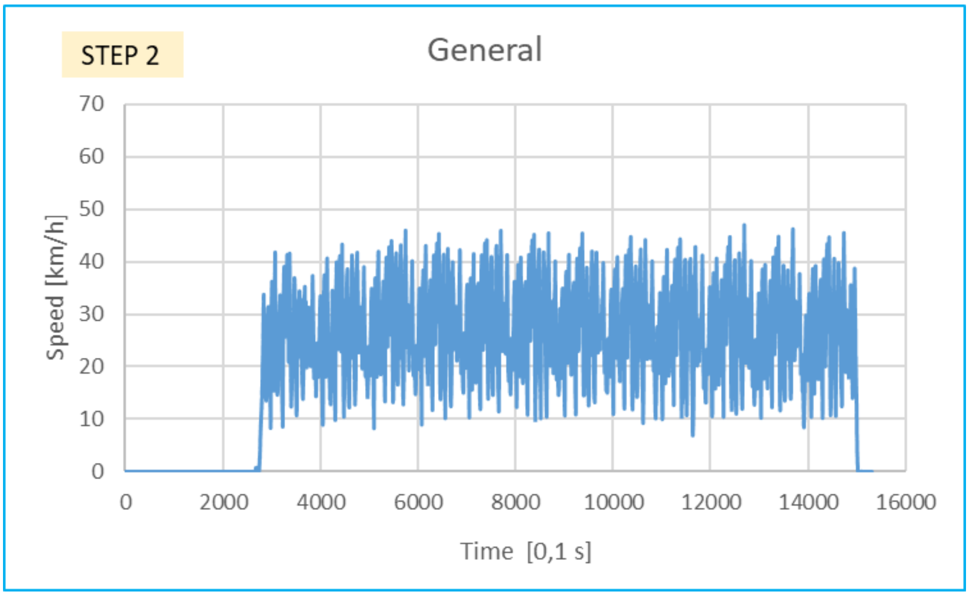
The machine was connected to a 200kg concrete weight which was drawn for 8 minutes, and then an additional 8 minutes were run by pulling with a double concrete weight (400 kg). Panel 5 of Figure 5 depicts the speed vs time operation of this step.

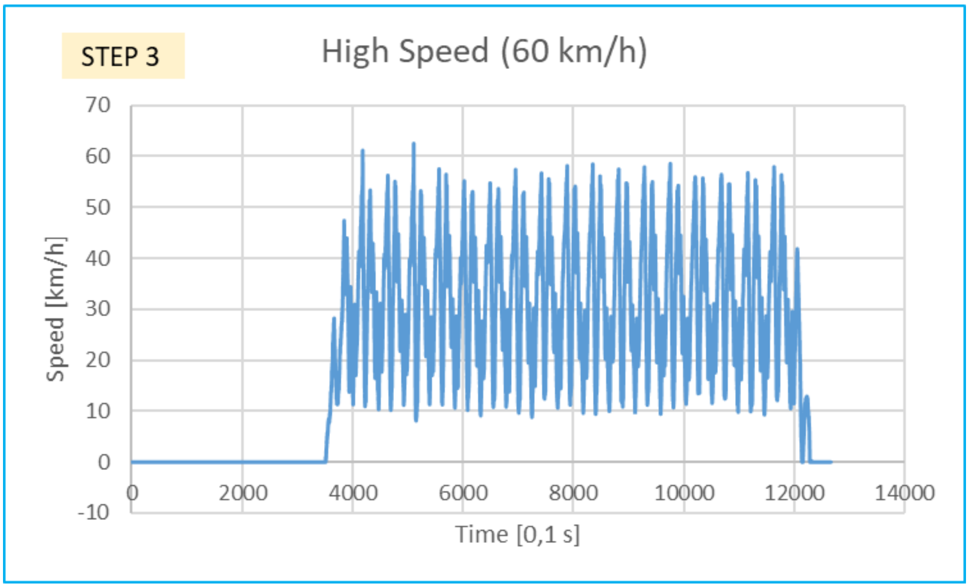
Emissions and vehicle parameters were always measured and recorded along the entire test performed.

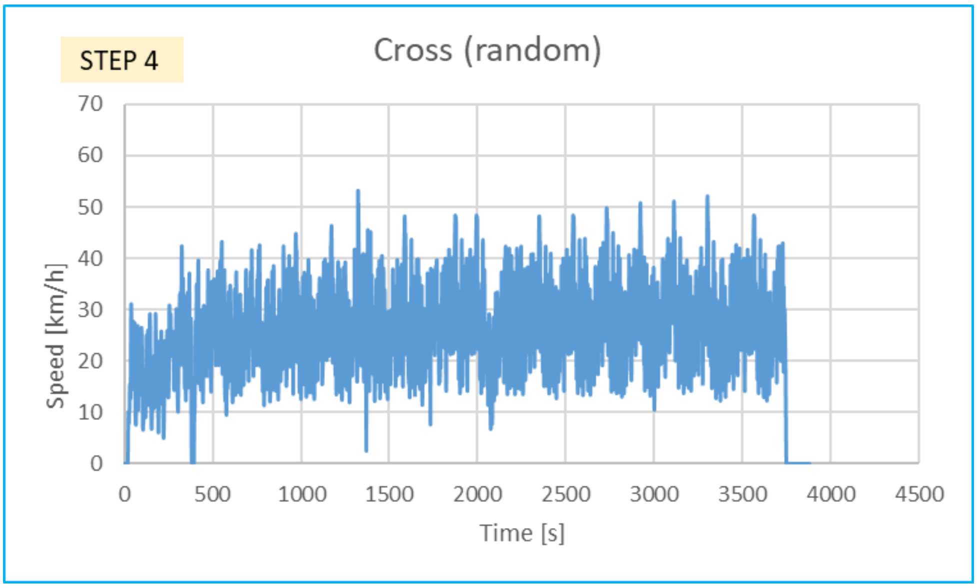
Figure 5. Speed profiles of the different tests performed in the field.

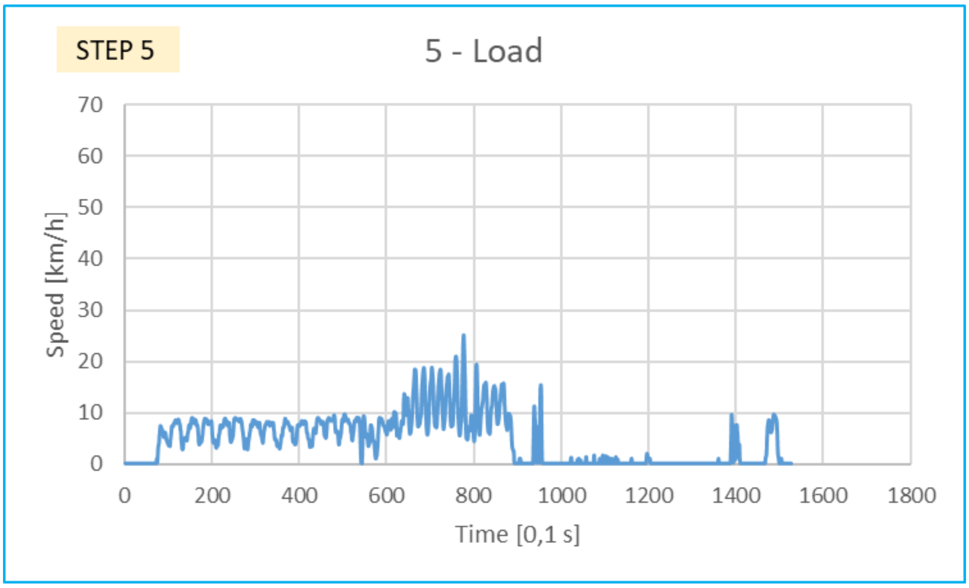


Source: JRC.Vela, 2017


STEP 2
General
Speed [km/h]
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [0,1 s]


STEP 3
High Speed (60 km/h)
Speed [km/h]
70
60
50
40
30
20
10
0
-10
0
2000
4000
6000
8000
10000
12000
14000
Time [0,1 s]


STEP 4
Cross (random)
Speed [km/h]
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Time [s]



Because of the similarities of step 4 (random test) with step 2 and the similarities of behaviour with other steps of that of step 5 (load), steps 4 and 5 have not been used to construct test cycles for further data processing. In what follows all the calculations and analysis have been done using an artificial test cycle constructed by combining (stitching) the data from steps 1, 2 and 3 in different sequences.

3.5 Data handling procedures and tools

3.5.1 Test data

The parameters that had to be recorded are listed in Table 6. The unit mentioned is the reference unit whereas the source column shows the measuring methods that were used.

3.5.2 Time alignment

The test parameters listed in Table 6 are split in 3 different categories:

a. Category 1: Gas analyser (THC, CO, CO2, NOx concentrations);

b. Category 2: Exhaust flow meter (Exhaust mass flow and exhaust temperature);

c. Category 3: Engine (Torque, speed, temperatures, fuel rate, vehicle speed from ECU).

According to the procedure developed for heavy-duty engines and in Reg. (EU) 2017/655, the time alignment of each category with the other categories has to be verified by finding the highest correlation coefficient between two series. All the parameters in a category are shifted to maximize the correlation factor.

The following parameters may be used to calculate the correlation coefficients to time-align:

1. Categories 1 and 2 (analyser and EFM data) with category 3 (Engine data): the (vehicle) speed from the GPS and from the ECU.

2. Category 1 with category 2: the CO2 concentration and the exhaust mass flow;

3. Category 2 with category 3: the CO2 concentration and the engine fuel flow.

The method was found suitable for NRMM engines.

Table 6. List of test parameters.

Parameter	**Unit**	**Source**
HC concentration [(1)]	ppm	Analyser
CO concentration [(1)]	ppm	Analyser
NOx concentration [(1)]	ppm	Analyser
CO_2 concentration [(1)]	ppm	Analyser
Exhaust gas flow	kg/h	Exhaust Flow Meter (hereinafter EFM)
Exhaust temperature	°K	EFM
Ambient temperature [(2)]	°K	ECU or Sensor
Ambient pressure	kPa	Sensor
Engine torque [(3)]	Nm	ECU or Sensor
Engine Speed	rpm	ECU or Sensor
Engine fuel flow	g/s	ECU or Sensor
Engine coolant temperature	°K	ECU or Sensor
Engine intake air temperature [(2)]	°K	ECU or Sensor
Vehicle longitude	degree	GPS
Vehicle latitude	degree	GPS
Vehicle Speed	km/h	GPS

Notes

[(1)] Measured or corrected to a wet basis

[(2)] Use the ambient temperature sensor or an intake air temperature sensor

[(3)] The recorded value shall be either (a) the net torque or (b) the net torque calculated from the actual percent torque and the reference torque, according to the SAE J1919-71 standard [R7]. The engine torque is not available on all vehicles.

Source: JRC.Vela, 2017

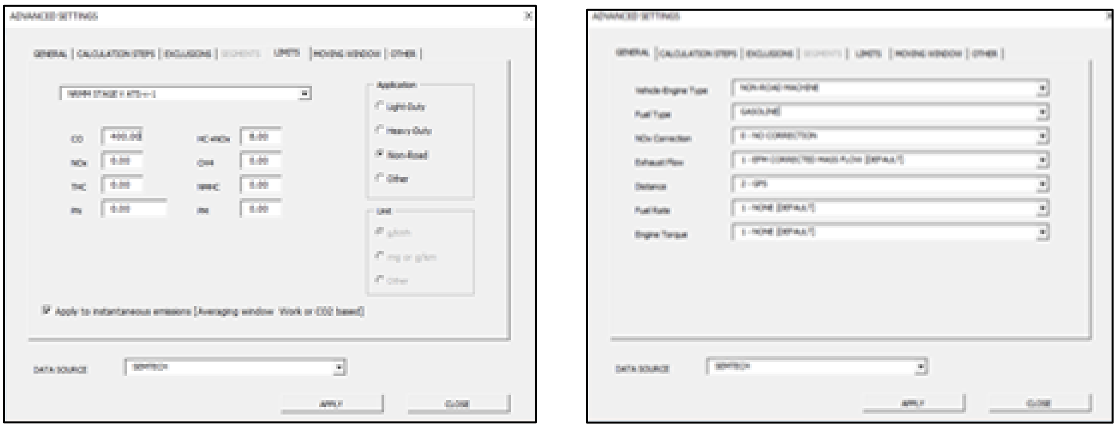
3.5.3 EMROAD©

Reporting templates and an automated data analysis (EMROAD 6.01) were used to ensure that all the calculations (of mass, distance specific and brake specific emissions) and verifications were done consistently throughout the pilot program. See Figure 6 as example of EMROAD's setting interface forms.

The standardized reporting templates included, for every test:

1. Second by second test data for all the mandatory test parameters;
2. Second by second calculated data (mass emissions, distance, fuel and brake specific);
3. Improved time alignment procedures between the different families of measured signals (analysers, EFM, engine);
4. Data verification routines, using the duplication of measurement principle, to check for instance the directly measured exhaust flow against the calculated one;
5. Averages and integrated values (mass emissions, distance, fuel and brake specific).

Figure 6. EMROAD setting interface forms.



Source: JRC.Vela, 2019

The calculations and the data screening were carried out using EMROAD©.

4 PEMS equipment

The lessons learned from the European PEMS pilot program for NonRoad Mobile Machinery engines can be summarised as follows.

4.1 Installation of PEMS equipment

Unlike in the case of HDV the installation and operation of the PEMS equipment as well as the definition of a test "trip or cycle" has been more complicated than expected (see later on in this report) due to the characteristics of the vehicles being tested in the ATVs NRMM PEMS Pilot Program.

The following is a non-exhaustive list of suggestions/recommendations extracted from the experience obtained in the field during the test program.

1. Installation of instruments should be made on a stable plate. The gas analyzer should be mounted using suitable damper to reduce the vibrations and shocks (see Figure 7).
2. Some degrees of freedom needs to be allowed for the EFM connection to the tail pipe, i.e. allow the instrument to move slightly without risking to damage tubes, cables (slack) and connections (military type), to compensate for vibrations and high accelerations.
3. EFM: possibility to use a flexible tube needs to be considered, maybe fixing the EFM onto the mounting frames (see Figure 8).

Figure 7. Mechanical works necessary to safely install the gas analyzer and the EFM.

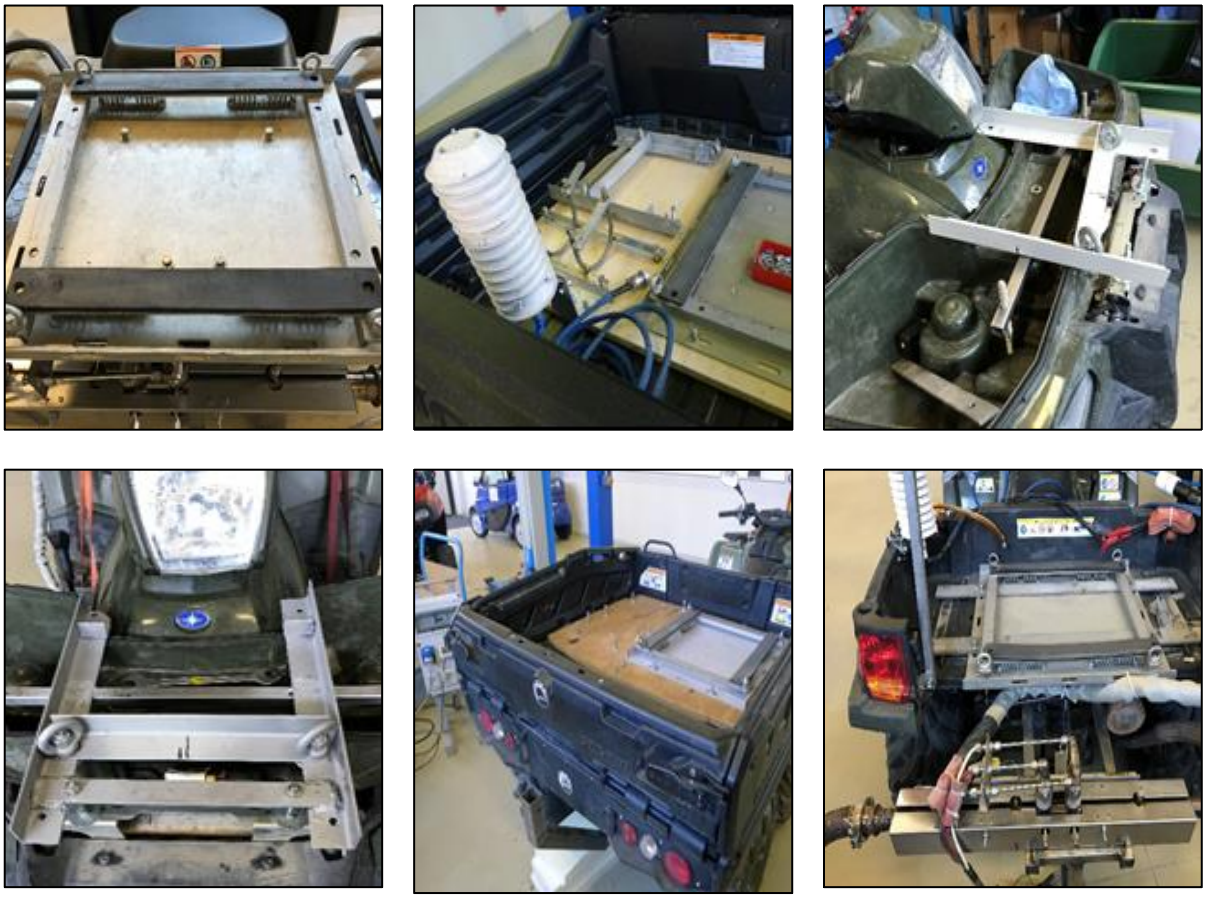


Figure 8. Mechanical works necessary to assembly the EFM. Detail of flexible pipe to connect the tail pipe.

4. To protect the equipment from dust, water, shocks, etc. (see Figure 9) it is necessary to use a suitable coverage (e.g. wrapped plastic or undeformable plastic sheet.

5. Instruments can be installed in the rack situated in the rear of the vehicle; therefore, a mounting platform is needed and modifications to the machine structure and exhaust tailpipe are difficult to avoid (see Figure 7 and Figure 8); the battery pack can be installed indifferently on the front rack (e.g. ATVs) or in the rear rack (e.g. SxS) according to the space at disposal. In case the vehicle is not supplied with a front rack, it is recommandable to create one to allocate the battery pack. (see Figure 7).

Figure 9. Coverage to protect the equipment from dust, water and shocks.

6. For safety reasons, the mounting platform in which is installed the equipment need to be secured to the vehicle: straps are considerated a good solution (see Figure 10).

Figure 10. How to safely install the gas analyzer and the EFM: use of straps is recommended.

7. Due to the outline and the reduced dimension of the rear rack, installing the equipment onto the platform of the vehicle (in particular on SxS) can prevent access to the gas analyzer components (e.g FID fuel bottle, filter).
8. Permanent machine modifications must be avoided as those will not be acceptable to the vehicle owner.
9. Access to the test equipment is necessary – either for the installation or for checks between tests –. Safety aspect needs to be considered.
10. Minimum power required: the use of batteries is recommended. Because batteries have a limited autonomy, they need to be replaced or recharged (gel battery ~30 kg).
11. FID fuel bottle: 0,5 liter bottle has an autonomy of about 6 hours (which must include warm-up and calibration) – Larger bottles could be used (1 liter) in case of enough space available. Recommendation: carefully protect the cylinder valve and adjustment pressure gauge.
12. Field testing: span gas bottles must be taken to the field to zero-span the gas analyzers, unless the measurements start from and finish in a workshop.
13. Avoid contamination of the air used to zero the gas analyzers (by the engine itself, the power generator or any other source) .
14. Recommendation: Remote monitoring of the instruments using Wifi is recommended.
15. Recommendation for the laptops: they need to be ruggedized, for high autonomy, dust and water proof, lighting of the monitor, etc.

4.2 Validation of PEMS with dynamometer test cell

The validation of PEMS instruments was carried out at the Vehicles Emissions laboratory (VELA) of the Suistainable Transport Unit (see Figures 11 and 12, Directorate for Energy, Transport and Climate, European Commission – Joint Research Centre, located in Ispra, Italy.

The chosen reference test bench was the VELA_1. The test cell equipped with a roller test bench, is capable to perform raw and diluited exhaust emission test and it suitable for light duty and motorcycles.

The climatized test cell is equipped with the following instruments and equipment (see Table 7):

Figure 11. View of VELA 1 from the control room.

Figure 12. ATV set for a test in VELA 1 with PEMS also installed.

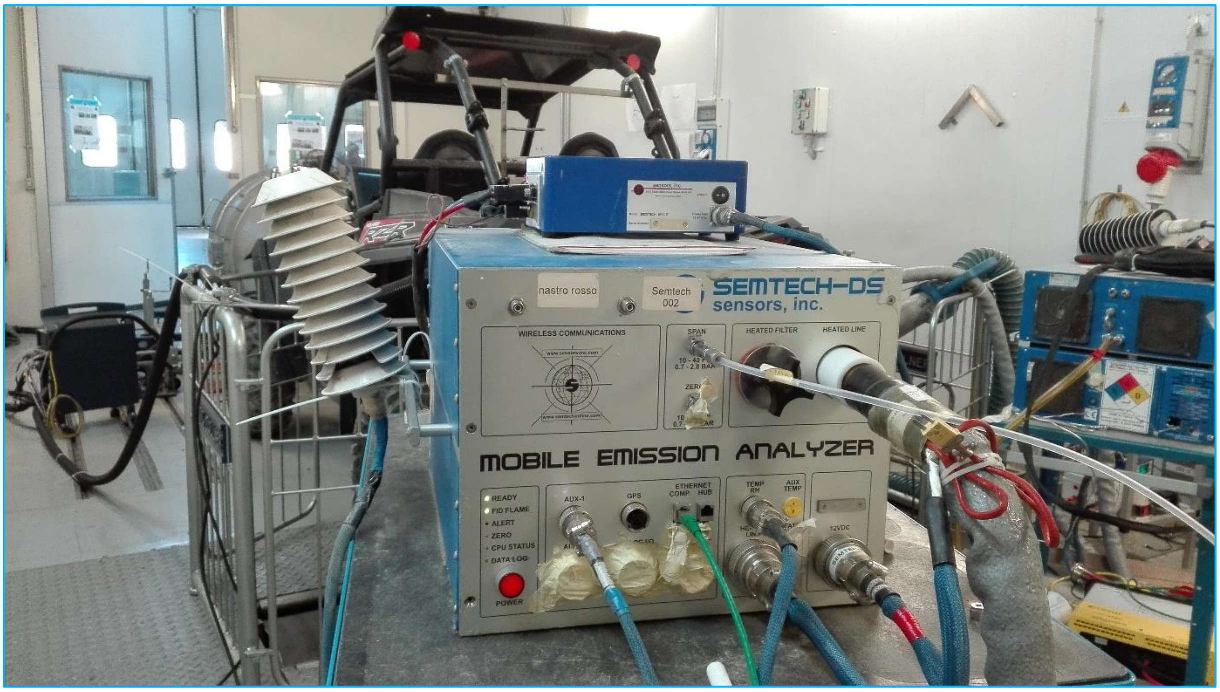


Table 7. Technical specification of the VELA_1 test cell.

EQUIPMENT	MANUFACTURER	PARAMETER
Chassis dynamometers	Zoellner GmbH	Diameter: 48'' Inertia: 150 - 3500 kg Max speed: 200 km/h
CVS (Constant Volume Sampling)	CGM	Flow range: 1.5 m^3/min to 11.25 m^3/min Separated tunnel for gasoline measurement (No PM) Bags, PTS, Blower
Exhaust Emission Analizer Bench 1 PreCat	AVL	AMA i60 R1(D1)
Exhaust Emission Analizer Bench 2 PostCat/Bag	Hartmann & Braun	CEBII (Euro2/3)
Software host computer	AVL/CGM	
Fuel Consumption	AVL KMA Mobile	KMA N2
Environment Stations	-	Air conditioning equipment - Test Cell
Exhaust Emission Analizer Bench 3 Dil	AVL	AMA i60 SII

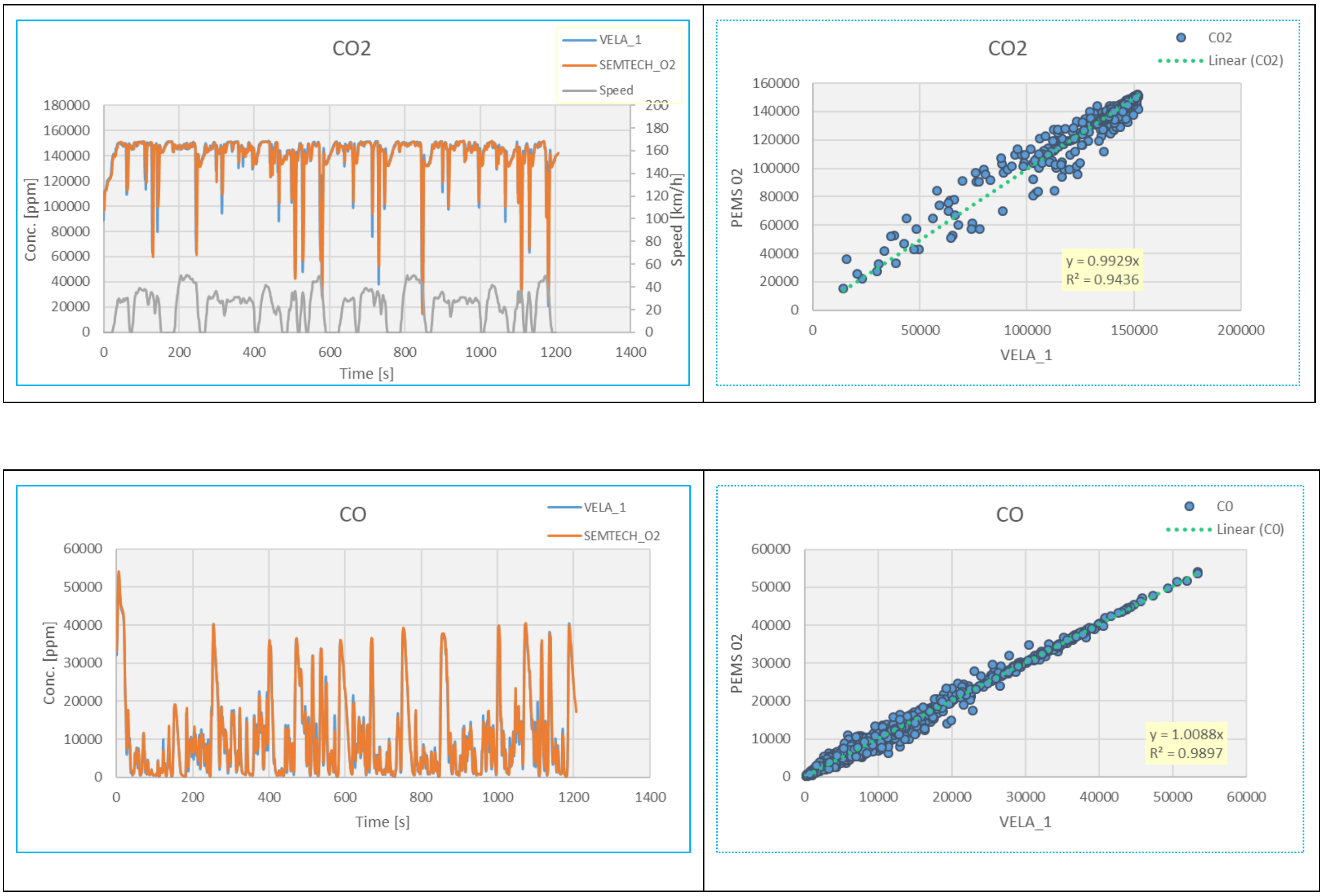
Source: JRC.Vela, 2017

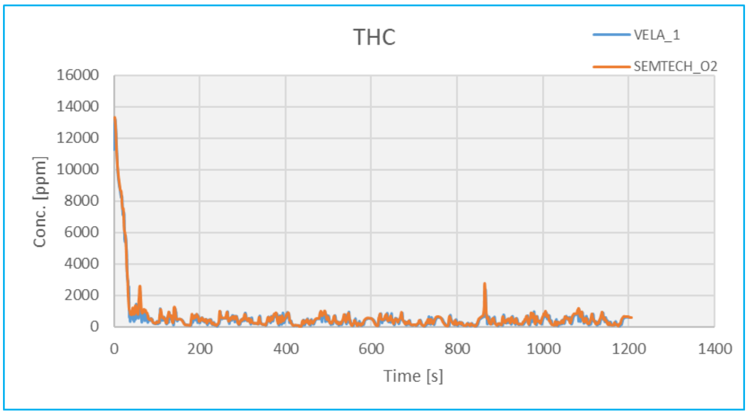
4.2.1 Validation of pollutant concentration: VELA 1 (reference test bench) vs PEMS 02 – Example 1

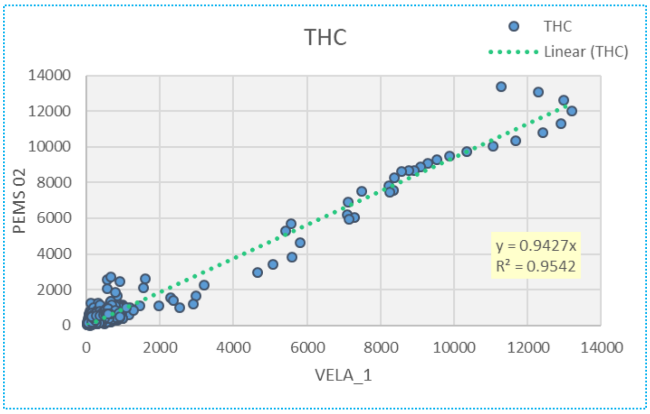
This test was performed to demonstrate the reliability in measuring the concentration of the pollutant in exhaust gas using PEMS instruments instead of a traditional CVS roller test bench. We tested the two SxS/SbS vehicles (vehicle C and Vehicle E). The test performed is a WMTC cycle starting at cold conditions. Figure 13 shows the very good correlation between the laboratory-base analytical instruments and PEMS measurements.

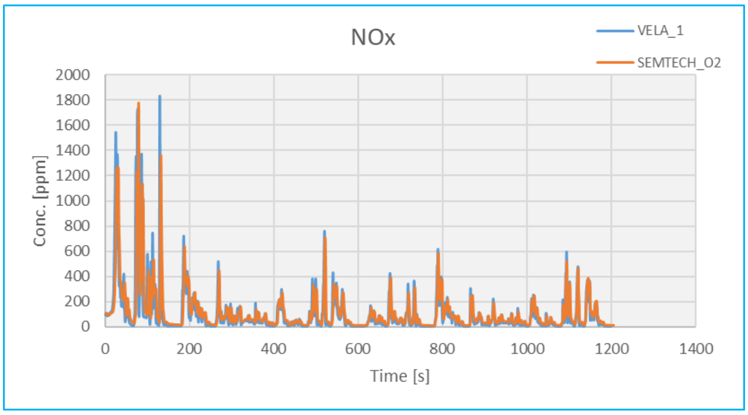
Figure 13. Correlation of the concentration values obtained by PEMS and the CVS of VELA_1 for vehicle C.

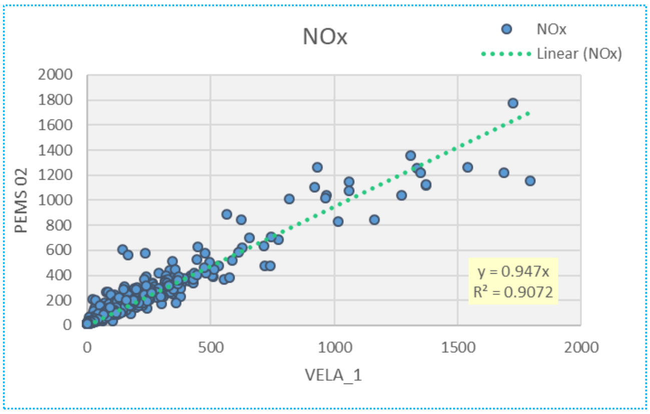
Test Item	COMPARISON VELA_1 vs PEMS_02
Vehicle	SxS
Model	Vehicle C
Test Date	20171031
Test detail	WMTC Cold

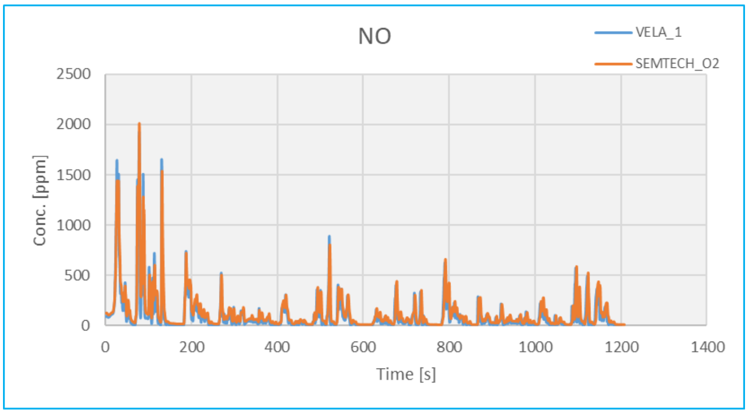


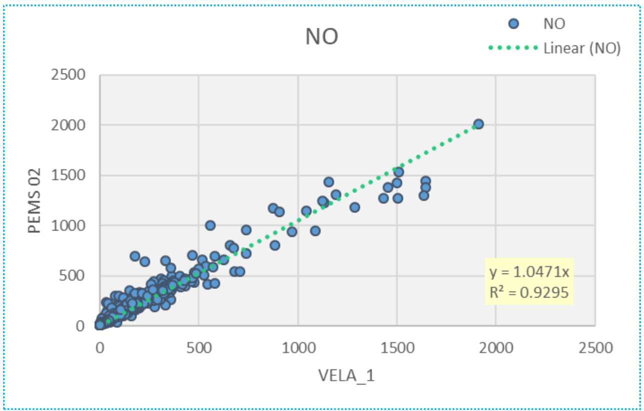

THC
VELA_1
SEMTECH_O2
Conc. [ppm]
Time [s]

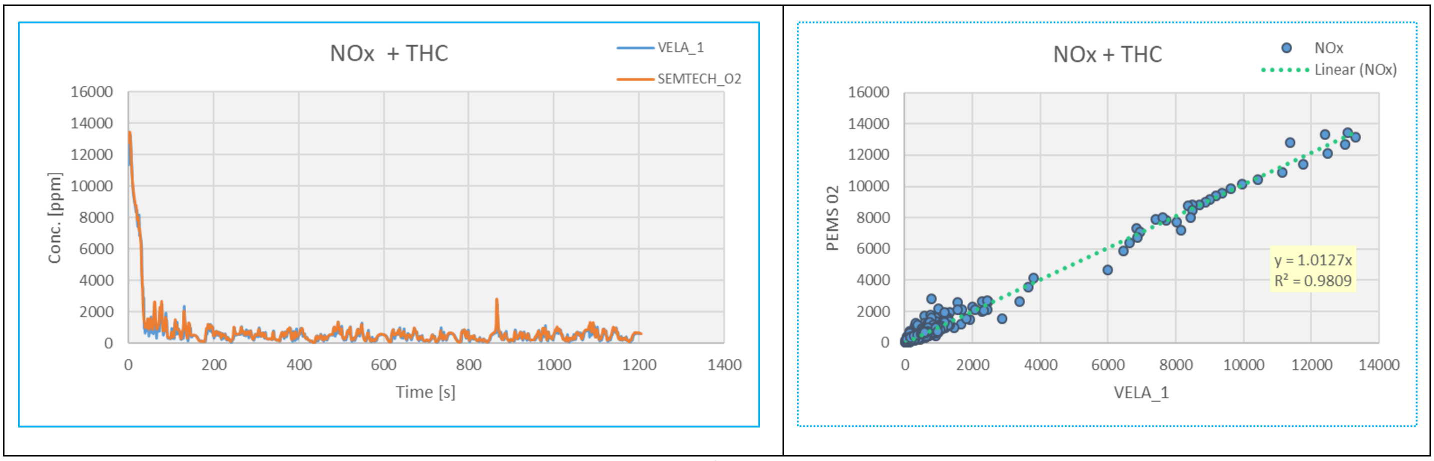

THC
THC
Linear (THC)
PEMS 02
VELA_1
y = 0.9427x
R² = 0.9542


NOx
VELA_1
SEMTECH_O2
Conc. [ppm]
Time [s]


NOx
NOx
Linear (NOx)
PEMS 02
VELA_1
y = 0.947x
R² = 0.9072


NO
VELA_1
SEMTECH_O2
Conc. [ppm]
Time [s]


NO
NO
Linear (NO)
PEMS 02
VELA_1
y = 1.0471x
R² = 0.9295



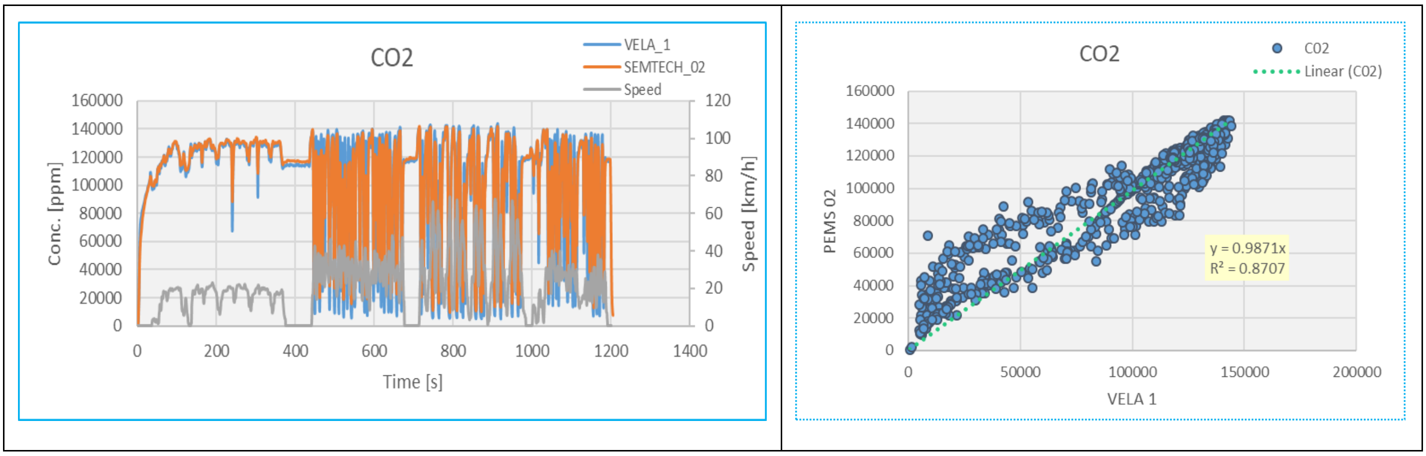
Source: JRC.Vela, 2017

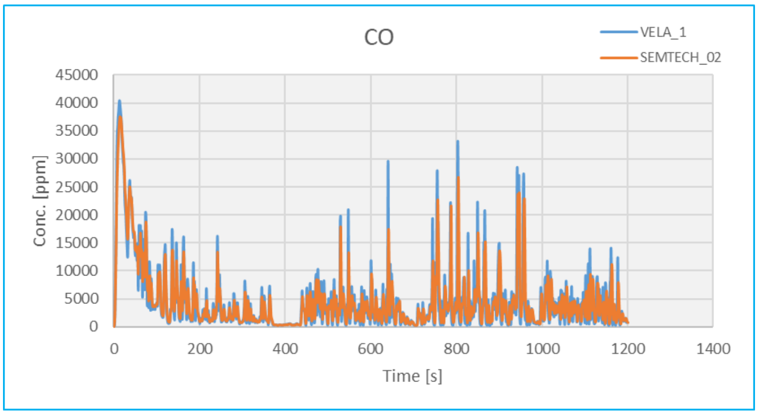
4.2.2 Validation of pollutant concentration: VELA 1 (reference test bench) vs PEMS 02 – Example 2

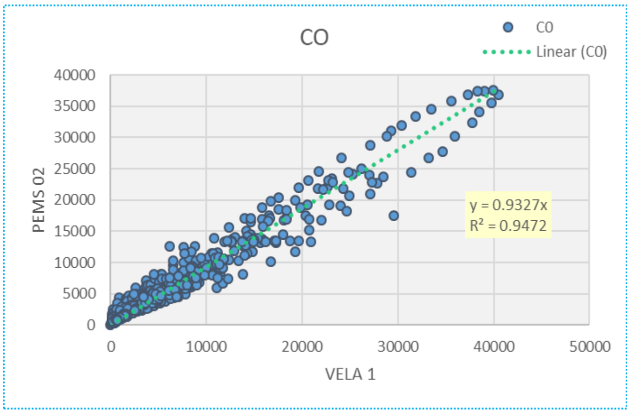
The following table and graph refers to a simulation on roller test bench of a field test, indicating that even in more dynamic condition the correlation is vey good (Figure 14). Also in this example the comparison is made between the reference test bench (VELA_1) and the PEMS equipment (PEMS_02).

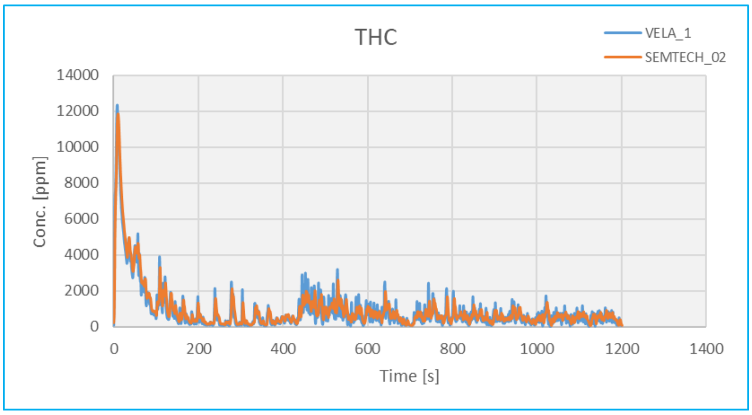
Figure 14. Correlation of the concentration values obtained by PEMS and the CVS of VELA_1 for vehicle E.

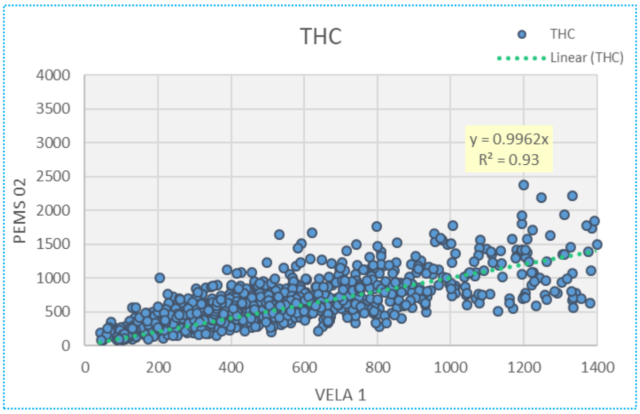
Test Item	COMPARISON VELA_1 vs PEMS_02
Vehicle	SxS
Model	Vehicle E
Test Date	20171204
Test detail	Field Test

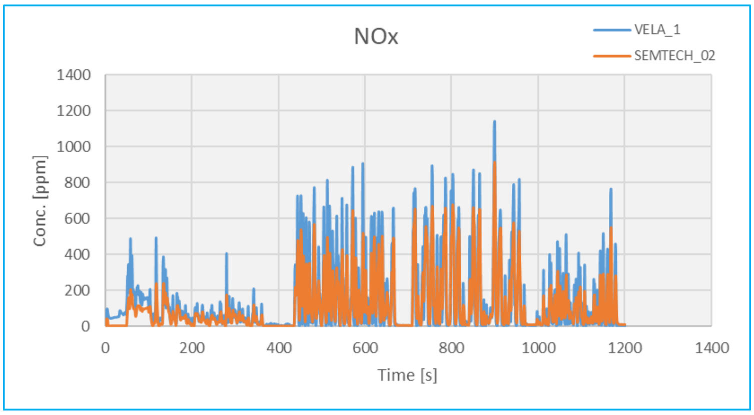


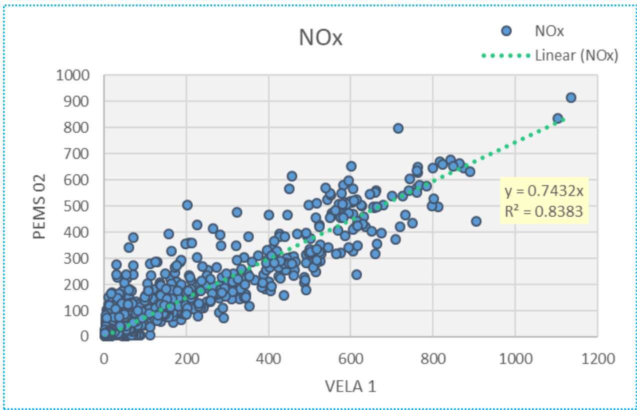

CO
VELA_1
SEMTECH_02
Conc. [ppm]
Time [s]

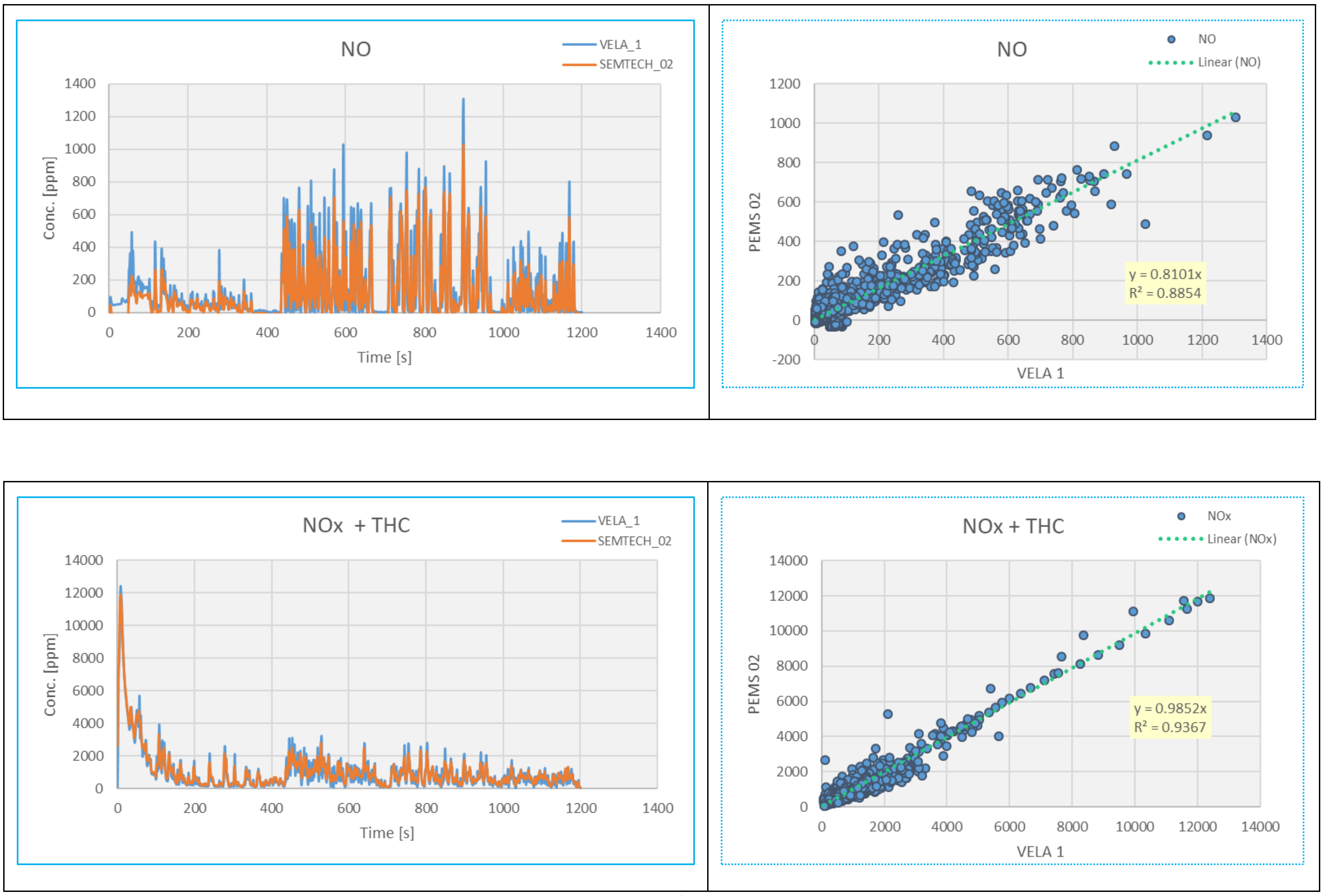

CO
CO
Linear (CO)
y = 0.9327x
R² = 0.9472
PEMS 02
VELA 1


THC
VELA_1
SEMTECH_02
Conc. [ppm]
Time [s]


THC
THC
Linear (THC)
y = 0.9962x
R² = 0.93
PEMS 02
VELA 1


NOx
VELA_1
SEMTECH_02
Conc. [ppm]
Time [s]


NOx
NOx
Linear (NOx)
y = 0.7432x
R² = 0.8383
PEMS 02
VELA 1



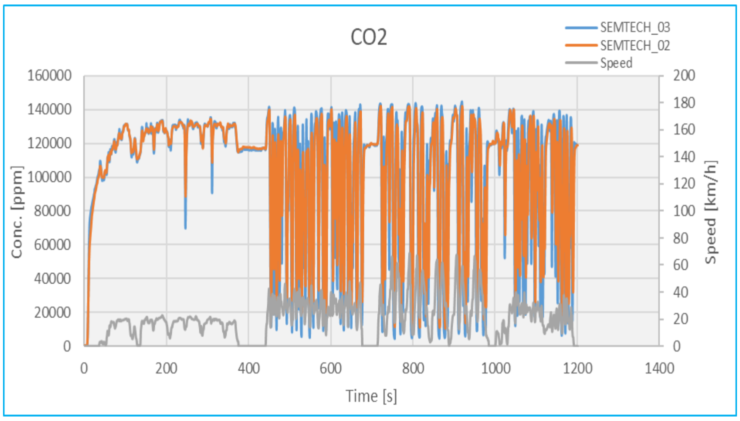
Source: JRC.Vela, 2017

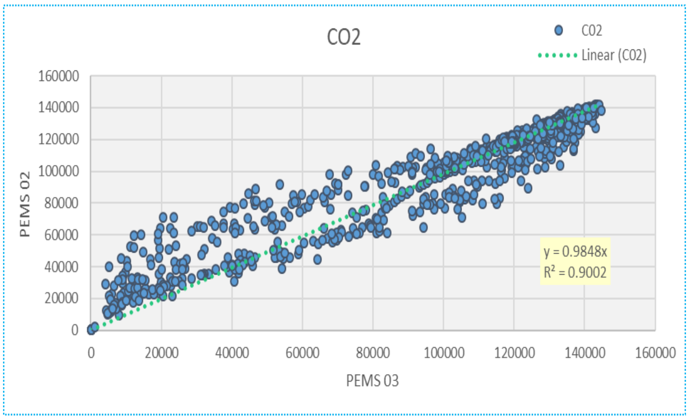
4.2.3 Correlation of PEMS (pollutant concentration): PEMS 02 vs PEMS 03

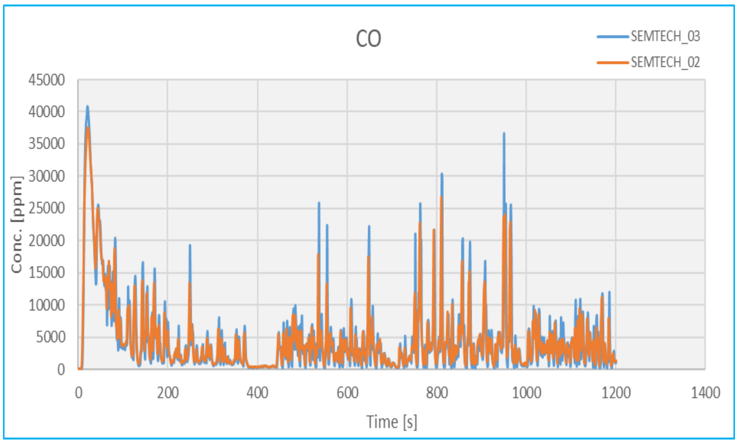
In the following table and graphs, the comparison is done between two differtent PEMS instruments, both used for the ATVs and SxS testing campaign (Figure 15). The correlation is similar to the one between the PEMS and the reference test bench (VELA_1). The test is still a field test simulation.

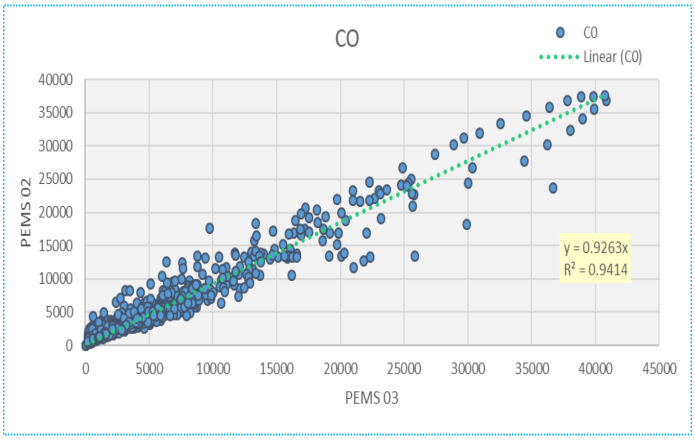
Figure 15. Correlation between two PEMS instruments used during the tests using vehicle E.

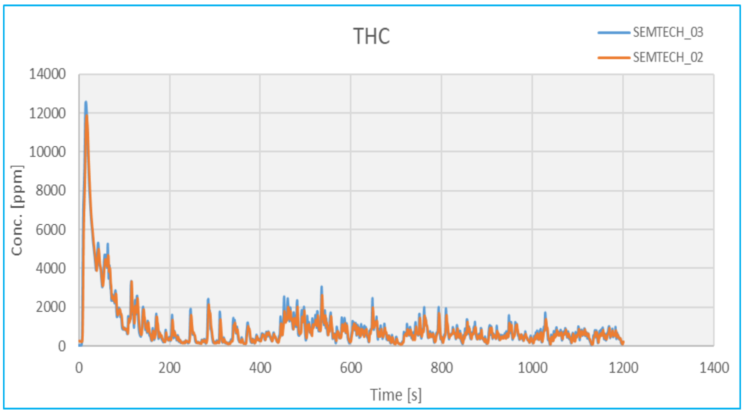
Test Item	PEMS_02 vs PEMS_03
Vehicle	SxS
Model	Vehicle E
Test Date	20171204
Test detail	Field Test

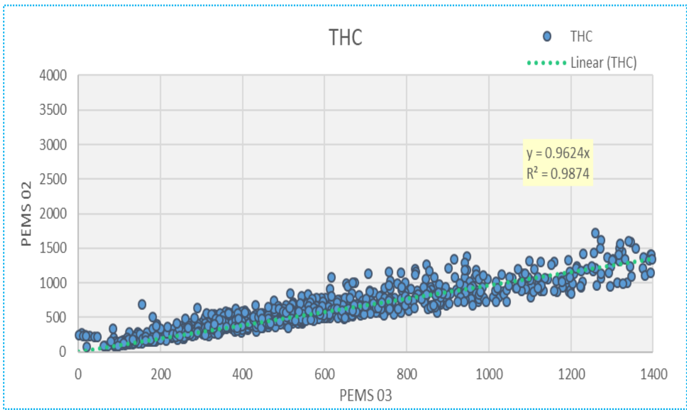

CO2
SEMTECH_03
SEMTECH_02
Speed
Conc. [ppm]
Speed [km/h]
Time [s]

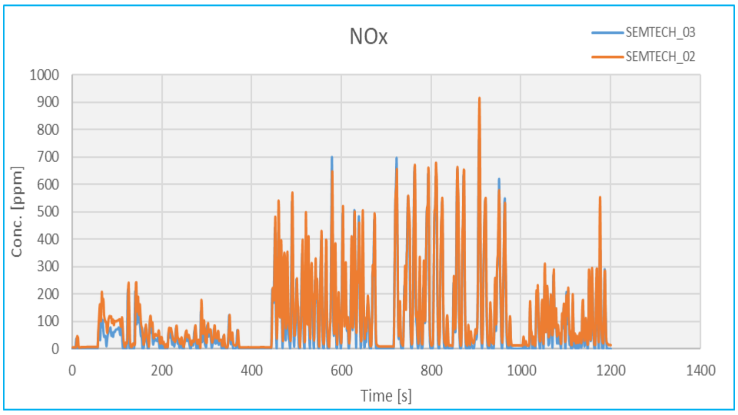

CO2
CO2
Linear (CO2)
y = 0.9848x
R² = 0.9002
PEMS 02
PEMS 03

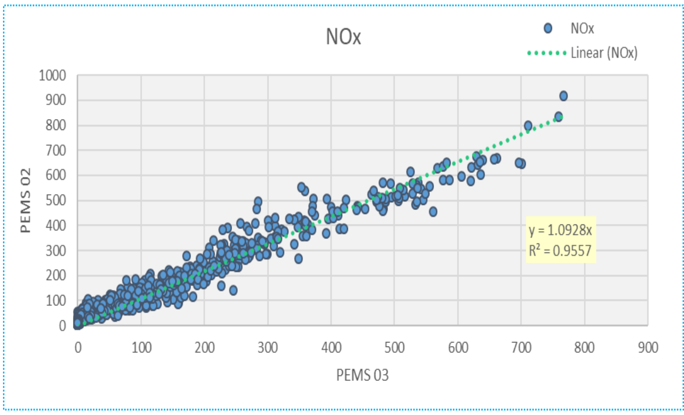

CO
SEMTECH_03
SEMTECH_02
Conc. [ppm]
Time [s]

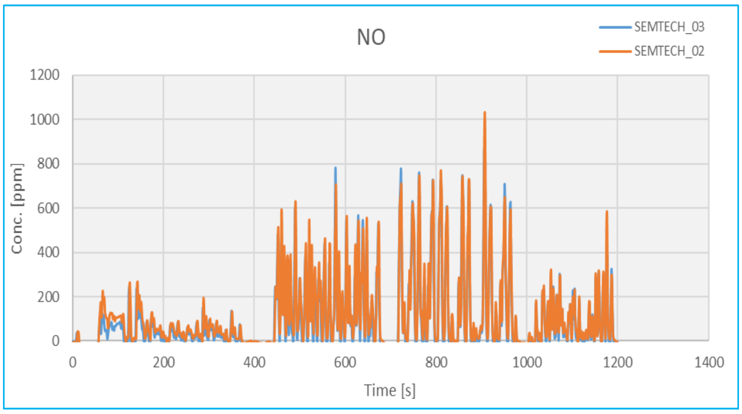

CO
CO
Linear (CO)
y = 0.9263x
R² = 0.9414
PEMS 02
PEMS 03

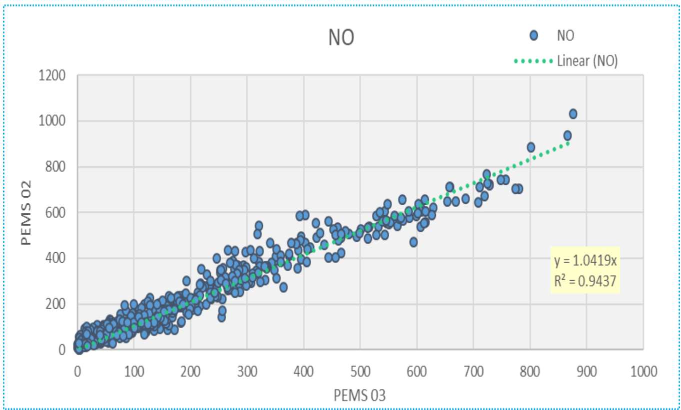

THC
SEMTECH_03
SEMTECH_02
Conc. [ppm]
Time [s]

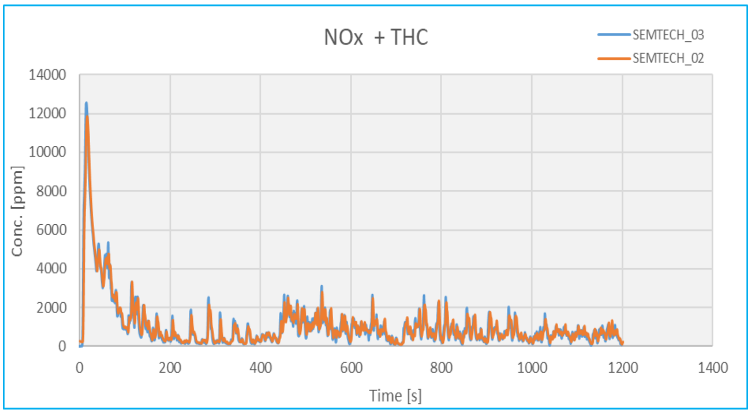

THC
THC
Linear (THC)
y = 0.9624x
R² = 0.9874
PEMS 02
PEMS 03

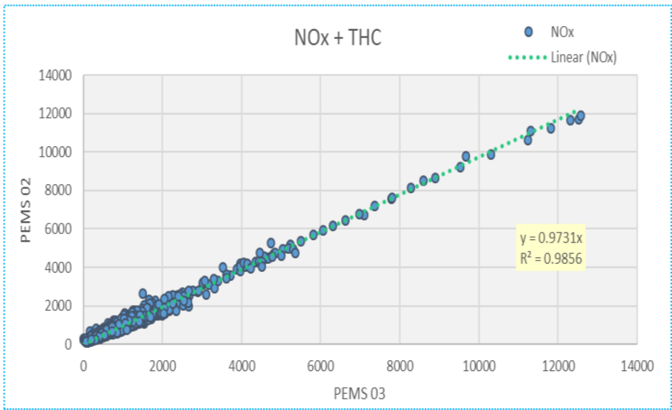












Source: JRC.Vela, 2017

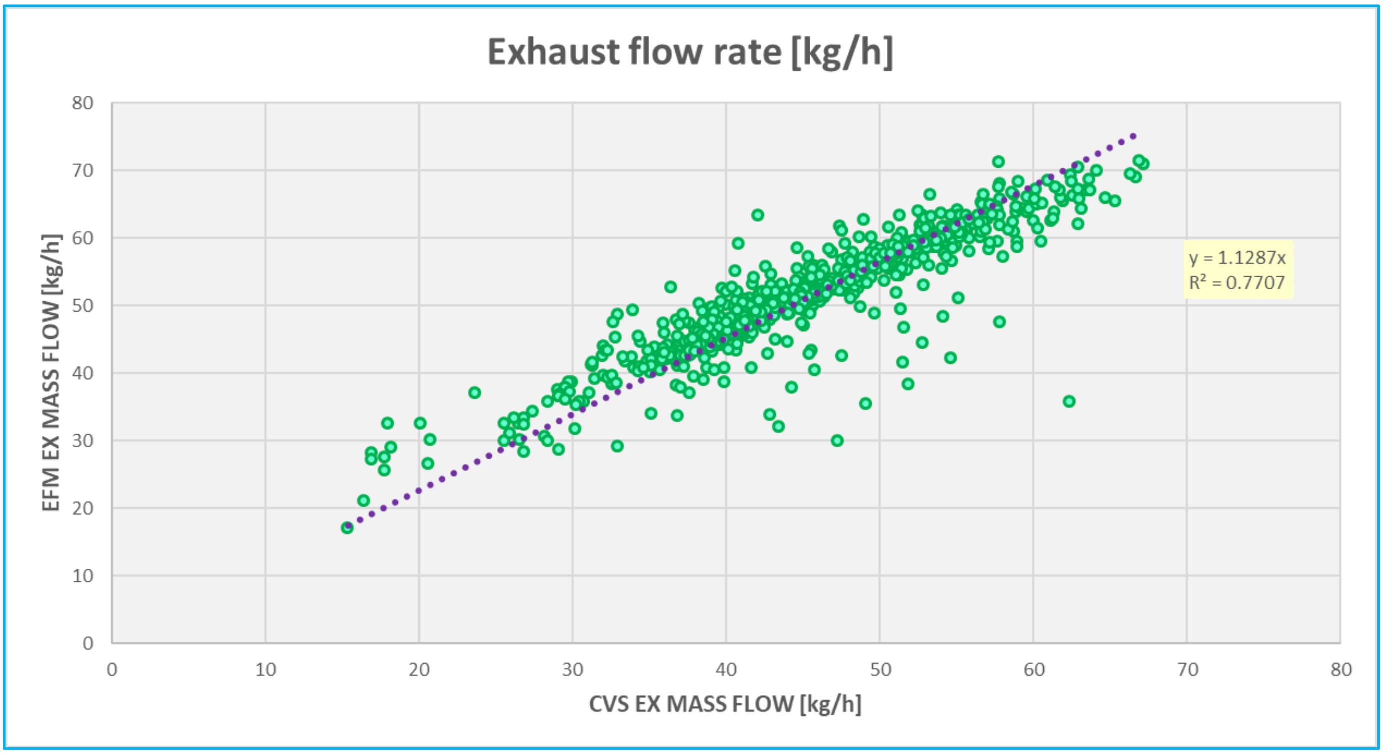
4.2.4 Validation of exhaust flow rate

Because of the mass emission is governed by the exhaust flow mass rate. The EFM used with the PEMS instruments has been correlated with the flow measured using a chassis dyno (CVS system). An ATV was installed on the rollers to undergo a WMTC test and the exhaust flow was measured by both systems, i.e. the EFM of the PEMS system and the CVS.

Figure 16, shows a good correlation of both systems, indicating an average difference of about 13%. This uncertainty will be the one governing the PEMS measurement uncertainty when an ISM test is performed.

Single cylinder engines operates with pulsations which are responsible for the uncertainty showed in this measurement. Therefore, the use of EFM having higher data acquisition rate is reconmended in order to minimised this effect.

Figure 16. Exhaust mass flow correlation between the PEMS EFM and those measured by the CVS.



Source: JRC.Vela, 2018

5 Reference magnitudes (i.e. work and CO_2)

Reference CO2

Reference work and CO_2 are obtained at the applicable test cycles:

a) The hot-start NRTC for engine categories NRE-v-3, NRE-v-4, NRE-v-5, NRE-v-6;

b) The LSI-NRTC for engine categories NRS-v-2b, NRS-v-3;

c) The discrete-mode or RMC NRSC for the corresponding engine category [not a) nor b)]

$$W_{ref} = \sum_{i=1}^{N} P_i \cdot \Delta t_i = \frac{1}{f} \cdot \frac{1}{3600} \cdot \frac{1}{10^3} \cdot \frac{2\pi}{60} \cdot \sum_{i=1}^{N} (n_i \cdot T_i)$$

$$m_{CO2,ref} = m_{CO2} / 1000$$

P_i = instantaneous engine power [kW]

n_i = instantaneous engine speed [rpm]

T_i = instantaneous engine torque [Nm]

W_{ref} = the reference work [kWh]

f = data sampling rate [Hz]

N = number of measurements [-]

m_{CO2} = mass of CO_2 for the test cycle

$m_{CO2,ref}$ = reference mass of CO_2

RMC = ramped modal cycle

W_{ref} and $m_{CO2,ref}$ determined from discrete-mode NRSC

$$W_{ref} = \sum_{i=1}^{N_{mode}} (P_i \cdot WF_i) \cdot \frac{t_{ref}}{3600}$$

$$m_{CO2,\,ref} = \sum_{i=1}^{N_{mode}} \frac{\left(q_{mCO2,i} \cdot WF_i\right)}{1000} \cdot \frac{t_{ref}}{3600}$$

Reference time t_{ref} is the total duration of the equivalent RMC

They are either 1800 s (cycles C1,C2, G1 and G2) or 1200 s (cycles D2, E2, E3, F and H)

W_{ref} = the reference work [kWh]

P_i = engine power for mode i [kW]

WF_i = weighting factor for the mode i [-]

t_{ref} = reference time [s]

$q_{mCO2,i}$ = mass flow of CO_2 for mode i [kg/s]

$m_{CO2,ref}$ = reference mass of CO_2

RMC = ramped modal cycle

The reference work and reference CO_2 mass of an engine type, or for all engine types within the same engine family, shall be those specified in points 11.3.1 and 11.3.2 of the addendum to the EU type approval certificate of the engine type or the engine family, as set out in Annex IV to Commission Implementing Regulation (EU) 2017/656[9];i.e. reference work and reference CO_2 mass of the parent engine

[9]Commission Implementing Regulation (EU) 2017/656

6 Working/non-working event validation

The new STAGE V[10] for Non-Road Mobile Machinery (NRMM) regulation prescribes the In-Service Monitoring (ISM) of NRMM. Based on the outcome of a Pilot Program conducted by the JRC in close collaboration with EUROMOT, the Commission has proposed a methodology to perform the ISM of NRMM for engines in the 56 to 560 KW power range (NRE-v-5 and NRE-v-6). The method includes among others the definition of working and not working events[11] based upon the instantaneous engine power being above or below 10% respectively of the maximum net power of the engine under test. The proposed method also describes the procedure for the determination of emissions using the Work based Averaging Window (WAW) or the CO_2 mass based Averaging Window (CO2AW) methods. While in the first case (i.e. WAW) the selection of working and not working events is straight forward, in the second case (i.e. CO2AW) is not so and indeed the proposed method does not address this point, making the method by the facto not applicable.

Valid events are based on the concept of working and non-working events. Non-working events are categorised as short non-working events (≤ D2) and long non-working events (> D2) (see the Table 8 for the value of D2).

The following marking steps are conducted:

- Non-working events shorter than D0 shall be considered as working events and merged with the surrounding working events (see the Table 8 for the values of D0).
- The take-off phase following long non-working events (> D2) shall also be considered as a non-working event until the exhaust gas temperature reaches 523 K. If the exhaust gas temperature does not reach 523 K within D3 minutes, all events after D3 shall be considered as working events (see the Table 8 for the values of D3).
- For all non-working events, the first D1 minutes of the event shall be considered as working event (see the Table 8 for the values of D1).

Table 8. Values for the parameters used to mark working and non-working events.

Parameter	Value [min]
D0	2
D1	2
D2	10
D3	4

Source: JRC.Vela, 2018

Appendix 4 to the Annex of Reg. (EU) 2017/655 includes the marking algorithm used for the definition of the working/non-working events

6.1 Calculation of engine instant equivalent power from the instantaneous CO_2 mass flow

This section proposes a methodology to calculate the instant equivalent power of the engine under ISM test from the instantaneous measured CO_2 mass flow, hence allowing the determination of working and not working events.

[10] Reg. (EU) 2016/1628

[11] 'event' means the data measured in an in-service monitoring test for the gaseous pollutant emissions calculations obtained in a time increment Δt equal to the data sampling period,

6.1.1 Equivalent power determination from CO_2 mass flow

<u>"Veline" approach for LDV:</u>

The Veline equation defines the CO_2 mass flow as function of the wheel power

$$CO_{2_i} = k_{WLTC} \times P_{w,i} + D_{WLTC} \qquad \text{(Eq.1)}$$

Where:

- CO_{2_i} = the instantaneous emitted CO_2 in [g/h]
- k_{WLTC} = slope of the Veline from WLTC, [g/kWh]
- $P_{w,i}$ = instant power at the wheel
- D_{WLTC} = intercept of the Veline from WLTC, [g/h].

"D" in the equation gives the CO_2 emissions at zero power output or in other words it represents the CO_2 emission value for idling at increased rpm (parasitic losses at engine speed that would result from a regression line with engine speed instead of CO_2).

<u>"Veline" approach for NRMM</u>

A simplified approach is proposed. In this case the "Veline" equation can be simplified by not considering the parasitic losses between the engine and the power to the wheel (i.e. the parameter D in eq. 1) <u>because the interest here is the power delivered by the engine rather that the power to the wheel.</u>

$$CO_{2_i} = k_i \times P_i \quad \text{(Eq.2)}$$

where P_i = instantaneous engine power

If we integrate for the whole duration of the test, then

$$\sum_{i=0}^{N} CO_{2_i} \times \Delta t_i = \sum_{i=0}^{N} k_i \times P_i \times \Delta t_i \qquad \text{(Eq. 3)}$$

We can consider that k_i is the same constant for each point and equal to K, then the eq. 3 becomes:

$$\textstyle\sum_{i=0}^{N} CO_{2_i} \times \Delta t_i = K \times \sum_{i=0}^{N} P_i \times \Delta t_i \ \text{(Eq. 4)}$$

Where:

$\Delta t_i = \Delta t = 1/f$

f is the data sampling rate [Hz]

$\sum_{i=0}^{N} CO_{2_i} \times \Delta t_i$ is the total CO_2 emitted in the trip (cycle) and $\sum_{i=0}^{N} P_i \times \Delta t_i$ is the total work performed in the trip (cycle).

Eq.4 becomes:

$$CO_{2_t} = K \times W_t \quad \text{(Eq. 5)}$$

As eq. 5 should be true for any cycle, then is should also hold true for the regulatory cycle and hence we can find the value of K from the values obtained at Type Approval.

$$K_{NRC} = \frac{CO_{2_{NRC}}}{W_{NRC}} \text{ (Eq. 6)}$$

Where

$CO_{2_{NRC}}$ is the total CO_2 emitted by the engine in the regulatory cycle [g]

W_{NRC} is the total work performed in the regulatory cycle [kWh]

And K_{NRC} is the “veline” constant in [g/kWh]

The actual engine power shall be calculated from the measured CO_2 mass flow (Eq. 2) according to:

$$P_i = \frac{CO_{2_i}}{K_{NRTC}} \quad \text{(Eq.7)}$$

Equivalent power:

The equivalent values of instantaneous power can then be calculated from the emitted CO2 flow using Eq.7 and therefore the selection of working and not working event can be made on the basis of this calculated equivalent power.

6.2 Validation for the proposed method

In what follow the validity of the approach proposed above is tested in an ATV for which the power was available (power broadcasted by the ECU) and the values of the Work and CO_2 at type approval are known. The validation is made on two approaches: a) comparison of valid events using only the power threshold and, b) applying the working/non-working event algorithm.

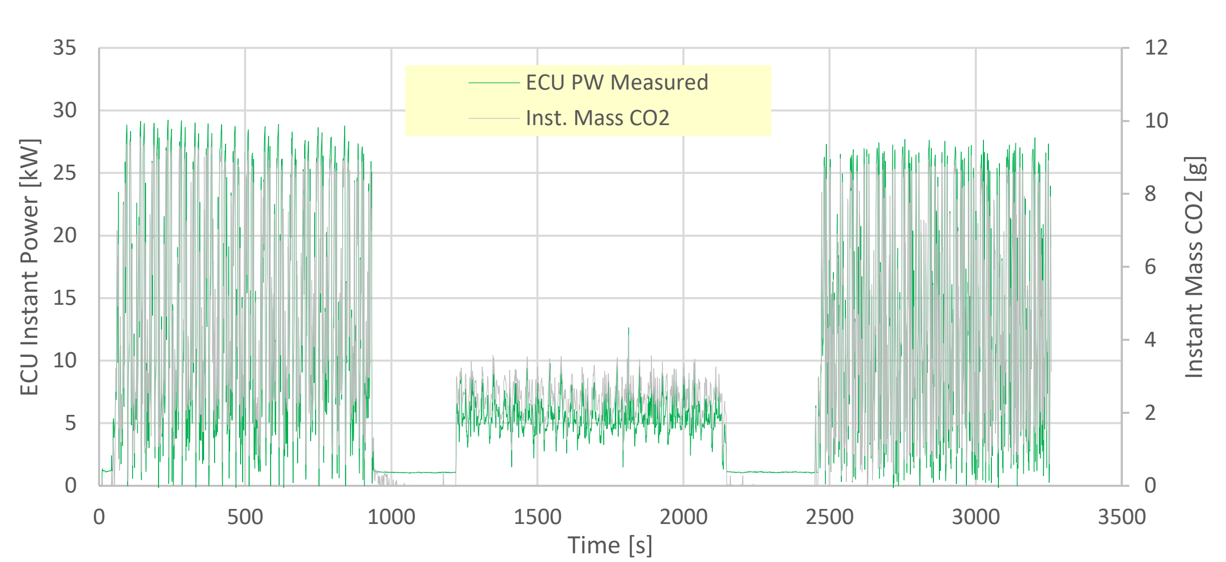
6.2.1 Comparison of events with P> 10% P_{max}

This example refers to a ATV vehicle with an engine whose maximun power is 39.6 kW at Type Approval. The NRSC reference work is 9.263 kWh and the reference CO_2 is 8139 g.

CO_2 values presented are obtained from on-board PEMS measurements. Whereas the power is calculated using the engine speed at actual torque provided by the ECU.

Figure 17 depicts the trace of Power and CO_2 for this machine/vehicle. It seems obvious that there is a linear relationship between both values.

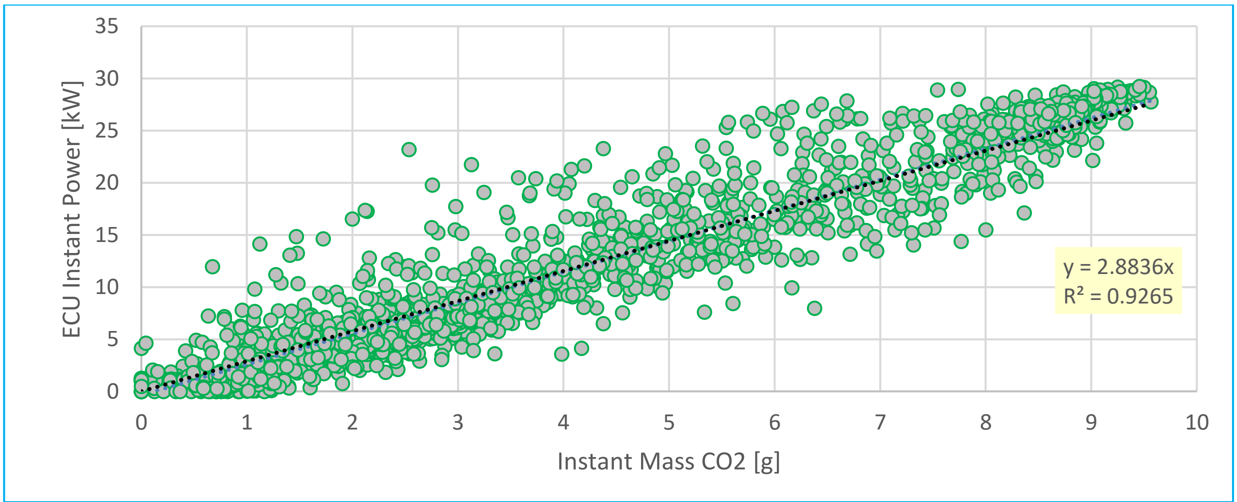
Figure 17. Power (from ECU) and CO2 trace for the tested vehicle.



Source: JRC.Vela, 2018

A better way of seeing the relationship is by plotting the instant power versus the instant CO_2 flow and check for linearity. Figure 18 depicts such plot and the least squares analysis shows a coefficient of determination r^2 of 0,93 which indicates a strong correlation.

Figure 18. Linear correlation between ECU Power and CO2.



Source: JRC.Vela, 2018

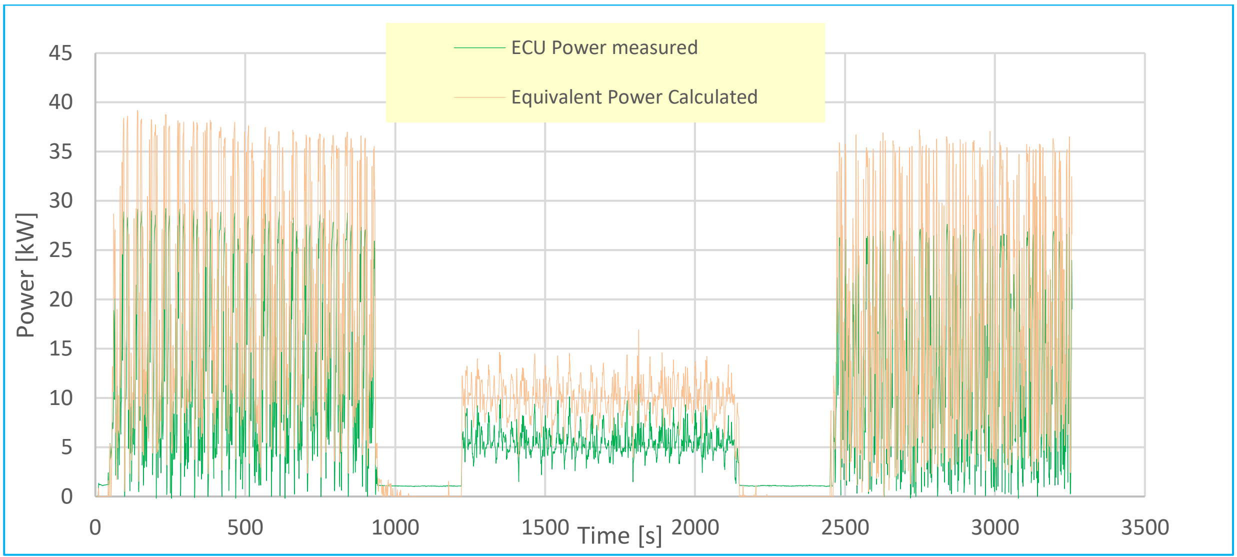
K can be calculated from the type approval values for this engine using Eq. 6: K= 878.66 g/kWh.

$$P_i = \frac{CO_{2_i}}{K_{NRTC}}$$ and considering the CO_2 flow is measured in g/s, then:

$$P_i = \frac{CO_{2_i}}{878.66} \cdot 3600\ [kW]$$

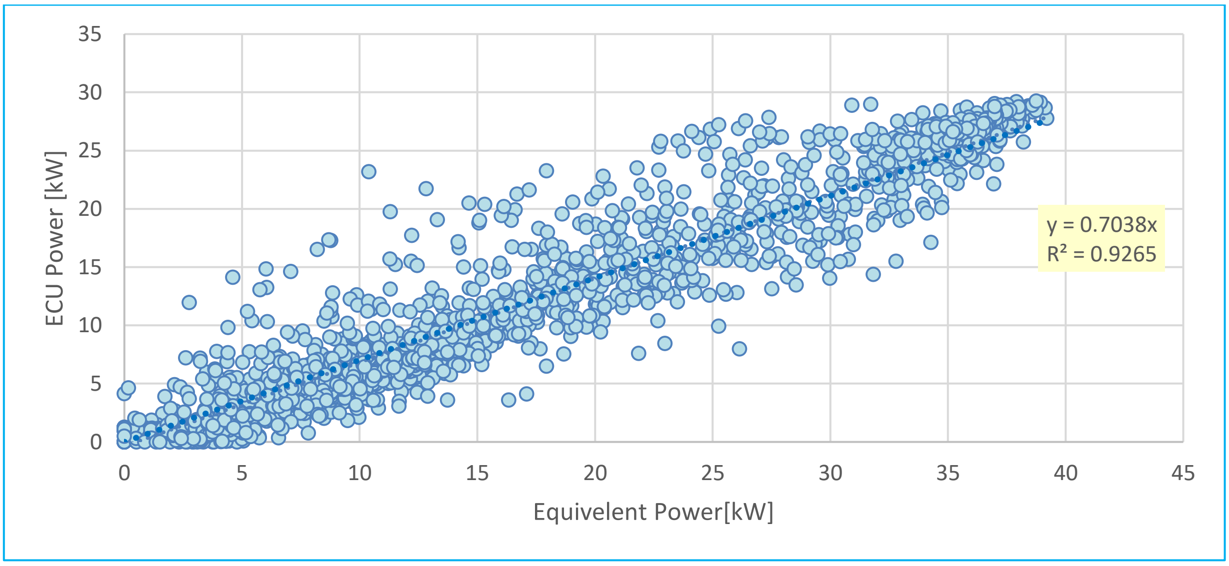
Figures 19 and 20 show the comparison between the power obtained directly from on-board measurements and the calculated values following the proposed methodology (equivalent power)

Figure 19. Power measured by ECU vs Power calculated using the "Veline" approach (equivalent power).



Source: JRC.Vela, 2018

Figure 20. Linear correlation between ECU Power and the Power calculated using the "Veline" approach (equivalent power).

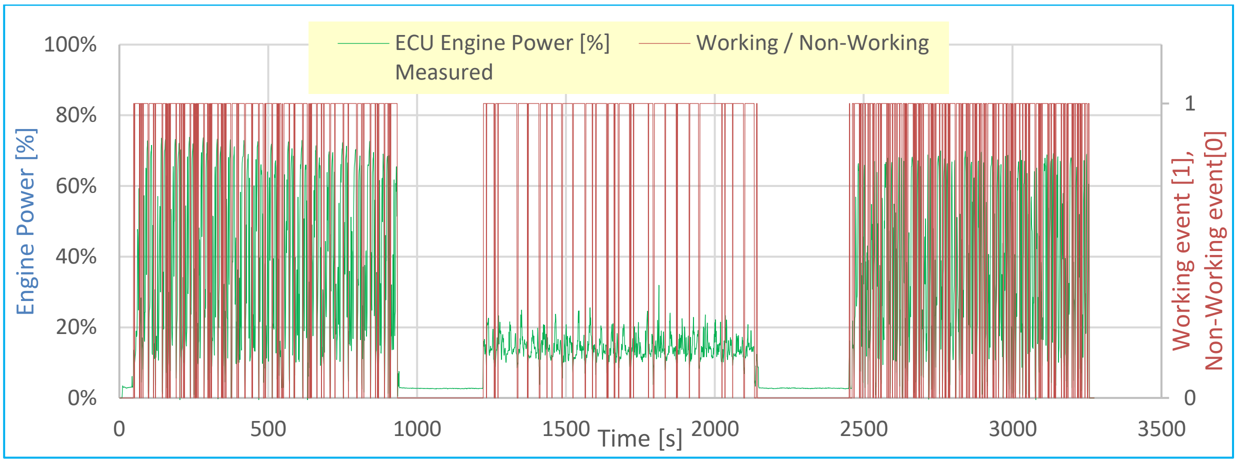


Source: JRC.Vela, 2018

The main purpose of this methodology is the selection of working and not working events for the case where the CO2BW method (see section 7) is used as emission determination procedure. Therefore, it is important to compare the number of events below 10% of the maximun net power of this engine for the case of power being measured (torque x rpm obtained from ECU) and for that of the calculated equivalent power using the proposed methodology.

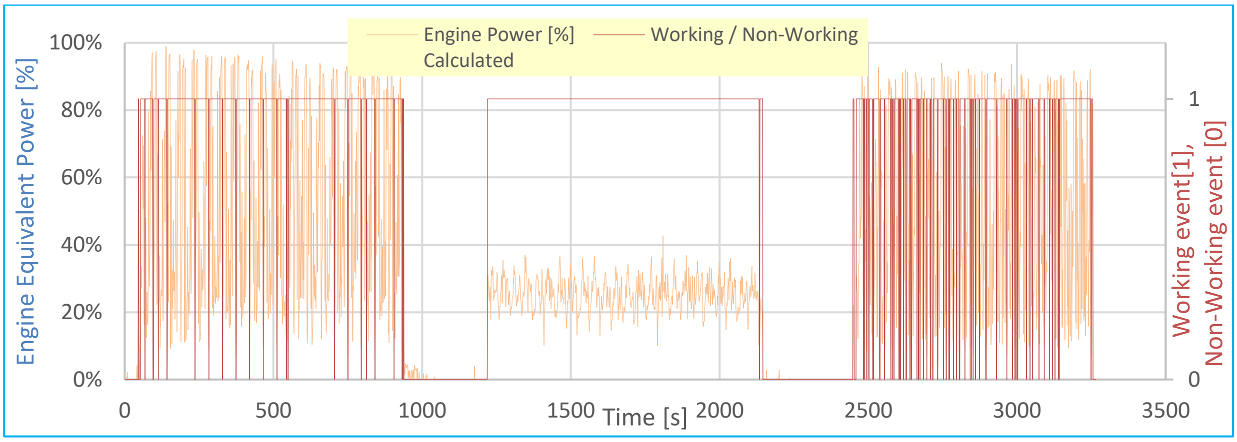
It is also important to find out wether the calculated equivalent power from the CO_2 will provide the same data distribution as in the case of the measured power once the procedure to determine working/non-working events is applied. (i.e. the application of the "machine work" marking algorithm in the EU Delegated legislation regarding monitoring of gaseus pollutant emission from in-service internal combustion engines installed in non-road mobile machinery/vehicle). See Figures 21 and 22 for reference.

Figure 21. Baseline calculation setting (ECU power measured).



Source: JRC.Vela, 2018

Figure 22. Baseline calculation setting (Equivalent engine power - calculated).



Source: JRC.Vela, 2018

Table 9 shows the number of events below 10% of the maximum power in terms of both absolute and percentage of total number of events for both cases.

Table 9. Difference between the power "measured" by the ECU and the equivalent power calculated using the "Veline" approach (Baseline data – P< 10%P_{max} excluded).

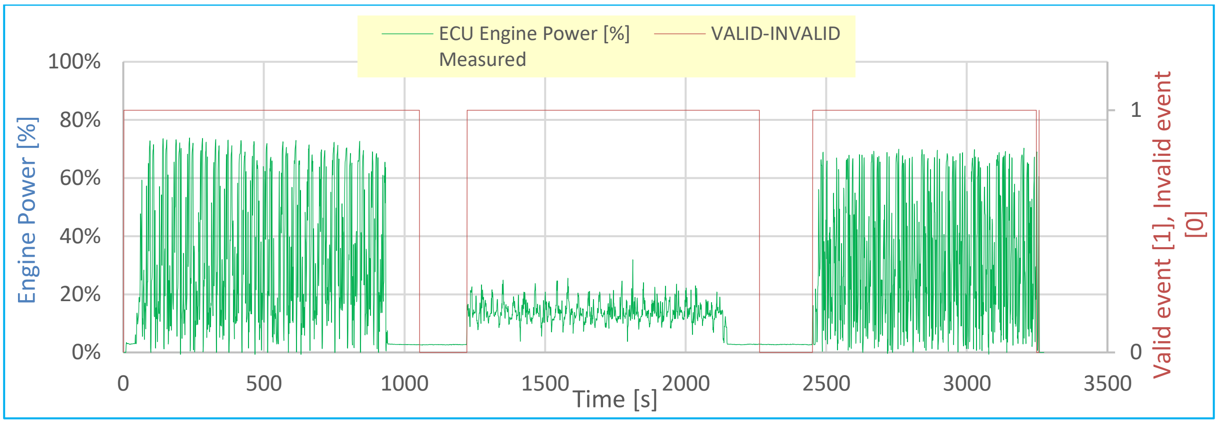
ESCLUSION: BASELINE (P <10% P_{max})	**ECU MEASURED**	**CALCULATED**
Total Number of events	3257	3257
Number of events with P<10% Pmax	995	756
% of non-working events	**30.55%**	**23.21%**

Source: JRC.Vela, 2018

6.2.2 Calculation using the working/non-working event algorithm

If we introduce the working/non-working events as defined above, taking into account the D0, D1, D2 and D3 parameters, the two power areas defined by the valid/invalid events line, become equivalent. See Figure 23 and 24.

Figure 23. Valid/invalid events using the measured power (ECU).



Source: JRC.Vela, 2018

Figure 24. Valid/invalid events using the calculated equivalent power.

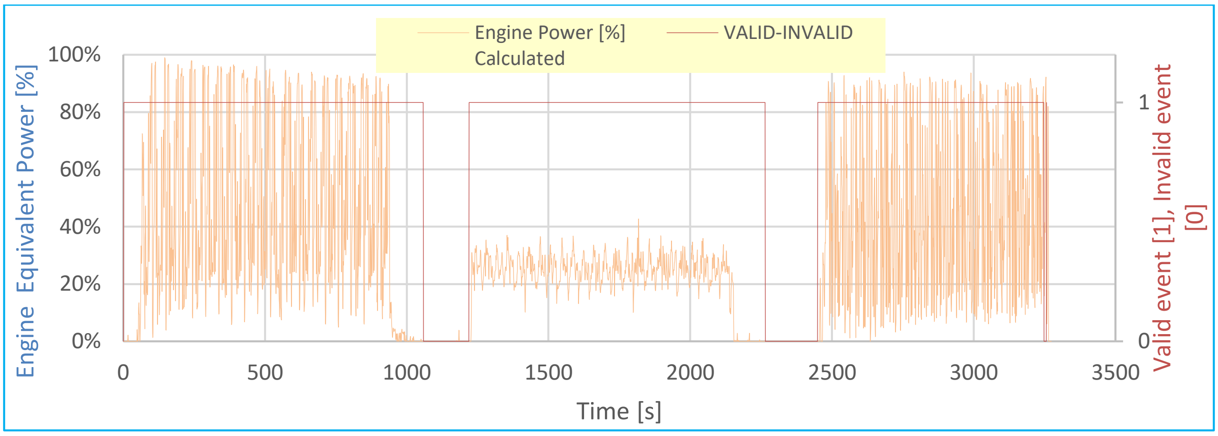


Table 10. Difference between the power "measured" by the ECU and the equivalent power calculated using the "Veline" approach.

ESCLUSION: BASELINE (P<10%) + WORKING/NOT WORKING EVENTS (D0/D1/D2/D3)	**ECU MEASURED**	**CALCULATED**
Total Number of events	3257	3257
Number of invalid events	368	356
% of invalid events	**11.30%**	**10.93%**

Source: JRC.Vela, 2018

The difference in percentage between the number of invalid events after applying marking algorithm is below 0.5%.

The marking algorithm applied to the test using the power (torque x rpm) broadcast by the ECU and the equivalent power calculated using the proposed methodology provides the same valid and invalid events with the same distribution (See Table 10).

Hence, it can be claimed that the methodology can be used for the case where the instant power of the machine during and in-service test is not known but only the CO_2 emission flow as it is the case for mechanically controlled engines (no ECU).

7 Emission Evaluation Methods for ISM

7.1 Introduction

In this European NRMM Pilot Program, some principles were adopted to assess the 'candidate' data evaluation methods:

The data analysis method in Reg. (EU) 2017/655 developed from the ISC of heavy duty engines, the so-called "averaging window methods" was considered as a baseline method which could require modifications or adaptations for the NRMM case.

7.2 Moving Averaging Window (MAW) method

The averaging window method is a moving averaging process, based on a reference quantity obtained from the engine characteristics and its performance on the type approval transient cycle. The reference quantity sets the characteristics of the averaging process (i.e. the duration of the windows). Using the MAW method, the emissions are integrated over windows while the power is averaged in the windows whose common characteristic is the reference engine work or CO_2 mass emissions. The reference quantity is easy to calculate or (better) to measure at type approval:

- In the case of work: the reference work is the one obtained in the certification test cycle.
- In the case of the CO_2 mass: from the engine CO_2 emissions on its certification cycle.

Using the engine work or CO_2 mass over a fixed cycle as reference quantity is an essential feature of the method, leading to the same level of averaging and range of results for various engines. Time based averaging (i.e. windows of constant duration) could lead to varying levels of averaging for two different engines.

The first window is obtained between the first data point and the data point for which the reference quantity (1 x CO_2 or work achieved at the regulatory cycle) is reached. The calculating window is then moved, with a time increment equal to the data sampling frequency (at least 1Hz for the gaseous emissions).

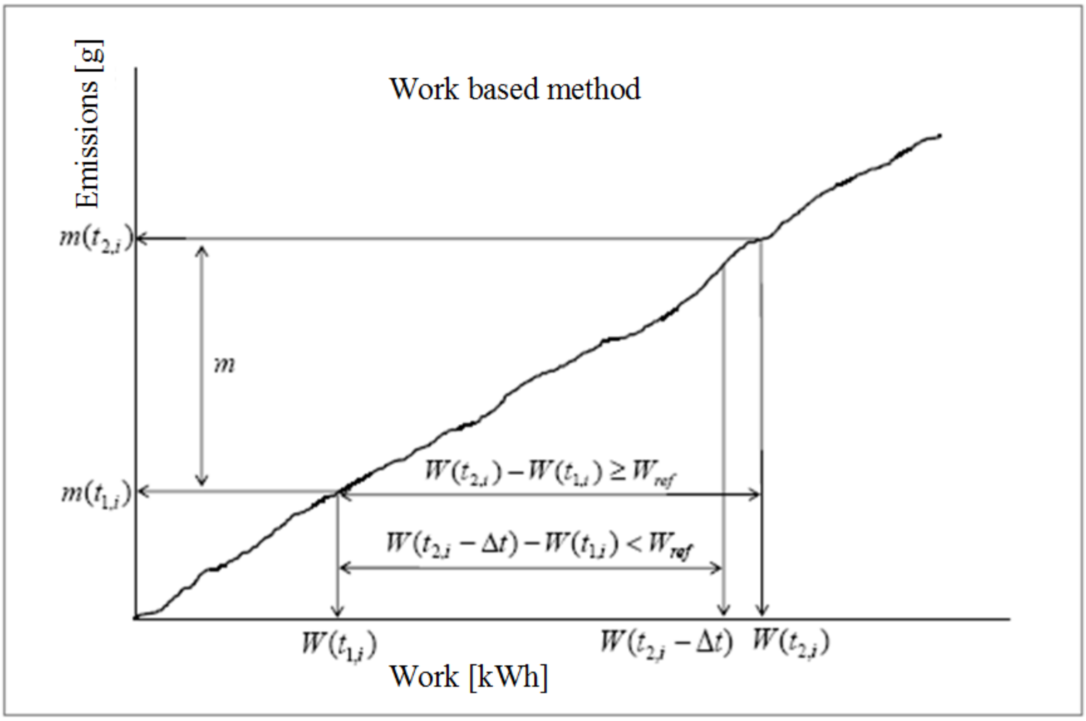
The following sections are not considered for the calculation of the reference quantity and the emissions of the averaging window due to invalidated data originated from:

- The periodic verification of the instruments and/or after the zero drift verifications;
- The data outside the applicable conditions (e.g. altitude or cold engine).

For the sake of completion, in the following section we recall the details of the calculation methods.

7.2.1 Work based method

Figure 25. Work based method.



Source: JRC.Vela, 2018

The duration $(t_{2,i} - t_{1,i})$ of the i^th averaging window is determined by:

$$W(t_{2,i}) - W(t_{1,i}) \geq W_{ref}$$

Where:

– $W(t_{j,i})$ is the engine work measured between the start and time $t_{j,i}$, [kWh];

– W_{ref} is the engine work for the homologation cycle, [kWh].

– $t_{2,i}$ shall be selected such that:

$$W(t_{2,i} - \Delta t) - W(t_{1,i}) < W_{ref} \leq W(t_{2,i}) - W(t_{1,i})$$

where Δt is the data sampling period, equal to 1 second or less.

7.2.1.1 Calculations of the brake specific gaseous pollutant emissions

The brake specific gaseous pollutant emissions e_{gas} [g/kWh] shall be calculated for each averaging window and each gaseous pollutant in the following way:

$$e_{gas} = \frac{m}{W(t_{2,i}) - W(t_{1,i})}$$

Where:

– m is the mass emission of the gaseous pollutant, mg/averaging window

– $W(t_{2,i}) - W(t_{1,i})$ is the engine work during the i^th averaging window, [kWh]

7.2.1.2 Selection of valid averaging windows

The valid averaging windows are the averaging windows whose average power exceeds the power threshold of 20 % of the maximum net engine power. The percentage of valid averaging windows shall be equal or greater than 50 %.

The test shall be considered void if the percentage of valid averaging windows is less than 50 %.

7.2.1.3 Calculations of the conformity factors

The conformity factors shall be calculated for each individual valid averaging window and each individual gaseous pollutant in the following way:

$$CF = \frac{e}{L}$$

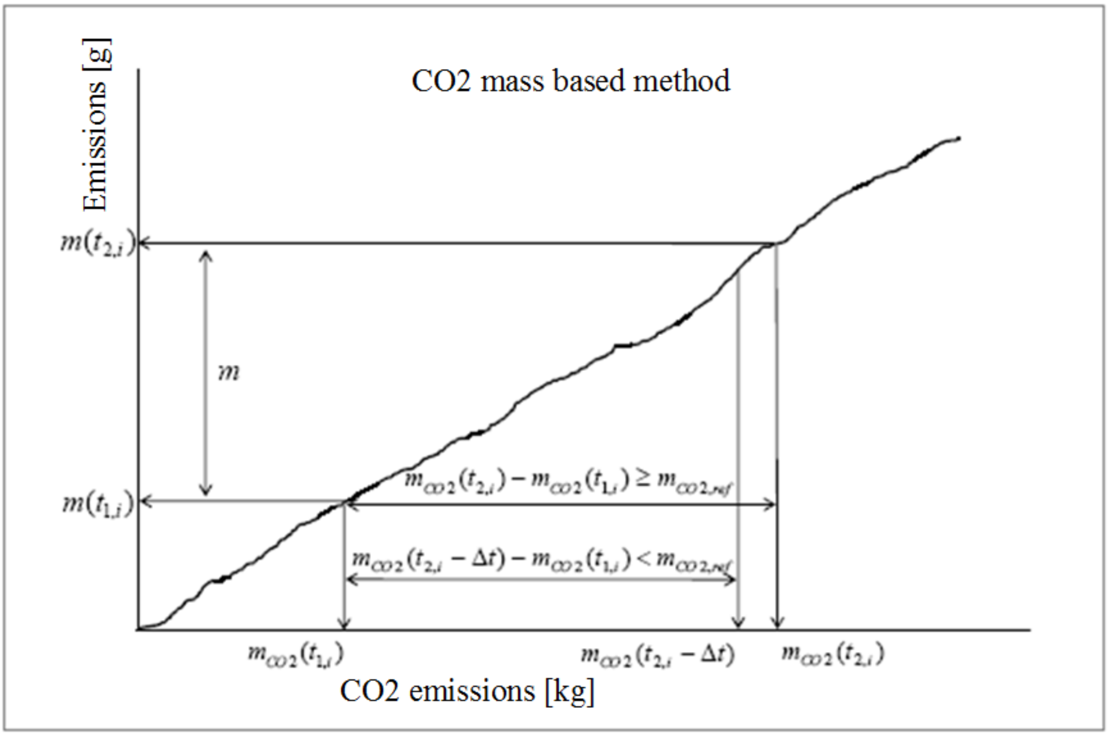
Where:

– e is the brake-specific emission of the gaseous pollutant, [g/kWh];

– L is the applicable limit, [g/kWh].

7.2.2 CO2 mass based method

Figure 26. CO2 mass based method.



Source: JRC.Vela, 2018

The duration $(t_{2,i} - t_{1,i})$ of the i[th] averaging window is determined by:

$$m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i}) \geq m_{CO2,ref}$$

Where:

– $m_{CO2}(t_{j,i})$ is the CO_2 mass measured between the test start and time $t_{j,i}$, [kg];

– $m_{CO2,ref}$ is the CO_2 mass determined for the homologation cycle, [kg];

– $t_{2,i}$ shall be selected such as:

$$m_{CO2}(t_{2,i} - \Delta t) - m_{CO2}(t_{1,i}) < m_{CO2,ref} \leq m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})$$

where Δt is the data sampling period, equal to 1 second or less.

The CO_2 masses are calculated in the averaging windows by integrating the instantaneous gaseous pollutant emissions calculated according to the requirements introduced in point 1 of Appendix 5 to the Annex of Reg. (EU) 2017/655.

7.2.2.1 Selection of valid averaging windows

The valid averaging windows shall be those whose duration does not exceed the maximum duration calculated from:

$$D_{\max} = 3600 \cdot \frac{W_{ref}}{0.2 \cdot P_{\max}}$$

Where:

$D_{\max}$ is the maximum averaging window duration, [s];

$P_{\max}$ is the maximum engine power, [kW].

The percentage of valid averaging windows shall be equal or greater than 50 per cent.

7.2.2.2 Calculations of the conformity factors

The conformity factors shall be calculated for each individual averaging window and each individual pollutant in the following way:

$$CF = \frac{CF_I}{CF_C}$$

with

$$CF_I = \frac{m}{m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})}$$ (in service ratio) and

$$CF_C = \frac{m_L}{m_{CO2,ref}}$$ (certification ratio)

Where:

– *m* is the mass emission of the gaseous pollutant, mg/averaging window;

– $m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})$ is the CO_2 mass during the ith averaging window, [kg];

– $m_{CO2,ref}$ is the engine CO_2 mass determined for the homologation cycle, [kg];

– m_L is the mass emission of gaseous pollutant corresponding to the applicable limit on the homologation cycle, [mg].

7.3 Calculation steps

To calculate the conformity factors, the following steps have to be followed:

- Step 1: (If necessary) Additional and empirical time-alignment.
- Step 2: Invalid data: Exclusion of data points not meeting the applicable ambient and altitude conditions: for the pilot program, these conditions (on engine coolant temperature, altitude and ambient temperature) were defined in the Regulation [R1]. Definition of valid and invalid event as explained above.
- Step 3: Moving and averaging window calculation, excluding the invalid data. If the reference quantity is not reached, the averaging process restarts after a section with invalid data.
- Step 4: Invalid windows: Exclusion of windows whose power is below 20% of maximum engine power.
- Step 5: Calculation of the CF for each of the valid windows.
- Step 6: Selection of the reference CF value from all the valid windows: i.e. 90^{th} cumulative percentile.

Steps 2 to 6 apply to all regulated gaseous pollutants.

8 Results

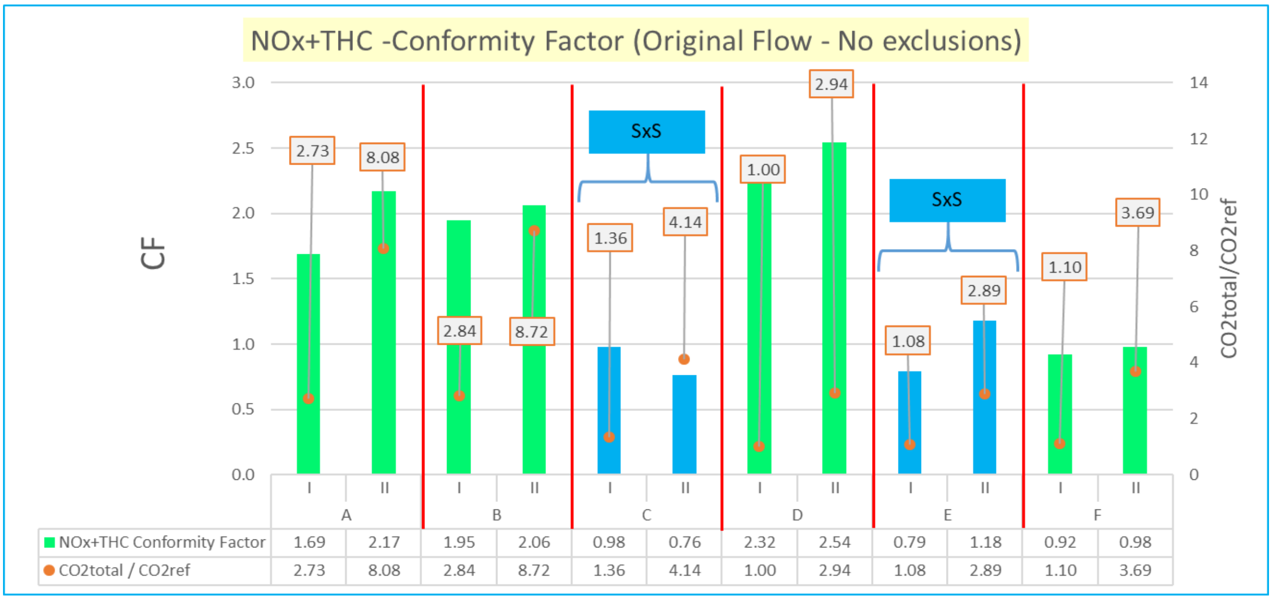
Figure 27 depicts the CF for the different ATS machines/vehicles participating in this pilot programme (ATV and SxS). The CF assigned to the different tests is the 90th cumulative percentile of all the valid window's CF.

In order to obtain a suitable amount of data with different test characteristics the tests has been combined using steps 1 to 3 of table 5 in one case and repeating that combination three times in the other. The CF values obtained for these combinations are those referred as I and II respectively in Figure 27.

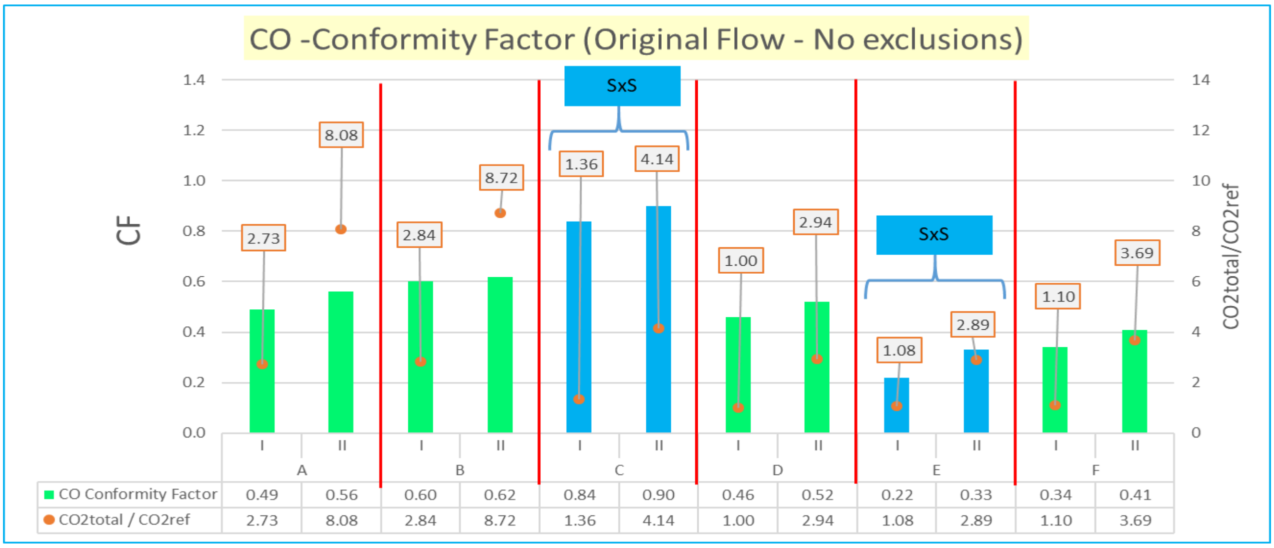
The difference in the lengths of the test defined as the number of accumulated reference parameter (i.e. the total CO_2 in the homologation cycle) indicates that a reasonable test length will be one with an equivalent duration between 3 to 5 time the reference value.

It is worthwhile to note that those engines mounting an aftertreatment system (TWC) generally has a lower CF as compared with those with none. This indicates that many ATS engines might need to have an aftertreatment system in order to comply with the Stage V regulation.

Figure 27. Conformity Factor for pollutant emission for the different ATS NRMM engines (no exclusion has been applied).



Source: JRC.Vela, 2019



Source: JRC.Vela, 2019

9 EFM measurements and relative corrections

9.1 Original measurements

The original measurement has been performed using a first EFM solution (EFM_JRC_1 from now on)

After a deeper investigation, it seemed that the reading capability of the used instruments was not adapt to the tested engines and machines/vehicles.

This is caused by the high amount of exhaust gas pulsation typical of single-cylinder and 2-cylinders engines.

An error in the measuring of the exhaust flow will obviously generate an error in the final definition of the Conformity Factor (CF) values.

In the present section, we will try to understand what the impact on CF is by starting from the original exhaust mass flow data.

In Annex 2, the possible issues of using an EFM based on a Pitot tube are addressed when it is used to measure a pulsating flow.

The Pitot tube flowmetering technique has been used to measure pulsating flow from a machine/vehicle engine exhaust. In general, flowmetering techniques that utilize differential pressure measurements based on Bernoulli's theory are likely to show erroneous readings when measuring an average flowrate of pulsating flow. The primary reason for this is the non-linear relationship between the differential pressure and the flowrate; i.e. the flowrate is proportional to the square root of the differential pressure. Therefore, an average of the differential pressure does not give an average of pulsating flow, unless fast response pressure transducers are used to measure the pulsating pressure. Then the pulsating differential pressure is converted to the flowrate while the pulsation is not averaged. An average flowrate is then calculated in the flowrate domain in order to maintain linearity before and after averaging. The results normally show a large amount of back and forth gas movement in the exhaust tube. This magnitude of pulsation can cause as much as five times higher erroneous results with the pressure domain averaging when compared to a flowrate domain averaging.

Base on a literature case (see Annex 2), in which a high speed logging instruments was not used, we can said that there is the concrete risk to overestimate the flow, as it is an average measure.

Moving from the above consideration, we corrected the measuring performed with a not enough fast response pressure transducers, using a comparison method. The mass flow measurement given by the CVS in VELA_1 was taken as reference.

As a first step, comparison tests between the performances of the EFM used for all the ATS campaign (EFM_JRC_1) and the performance of a second generation equipment (EFM_JRC_2) was made using the reference chassis dyno (VELA_1) and a machine/vehicle similar to F in table 2. These tests allow understanding the relationship between both instruments.

The tests were:

a) A equivalent field test in which the measurement of EFM_JRC_1 and EFM_JRC_2 are compared indirectly to the reference equipment: Vela_1

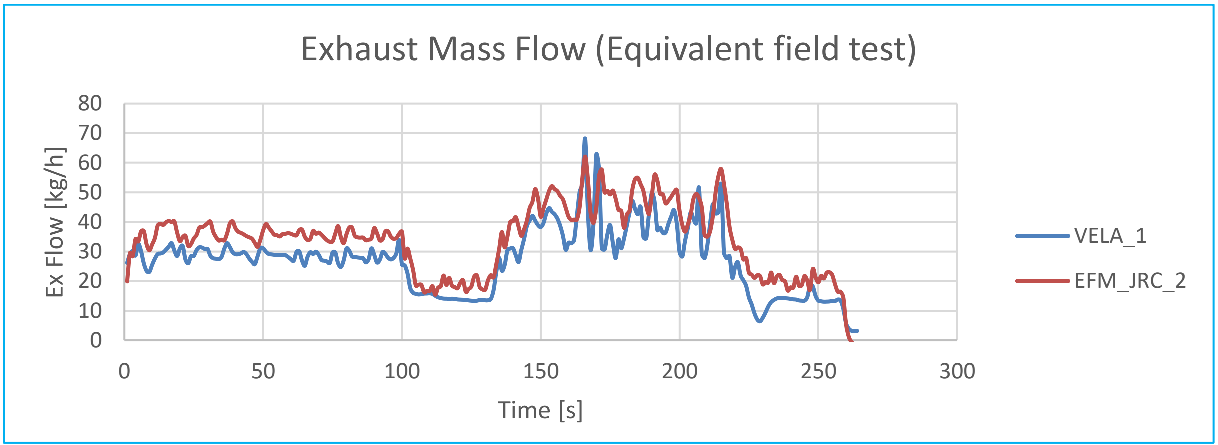
b) A regulatory transient test cycle (WMTC) in which the measurement of EFM_JRC_1 and EFM_JRC_2 are compared together with the reference equipment: Vela_1

As second step, the possibility of applying a reliable correction to the measurements using the EFM_JRC_1 was explored. In the following section, two investigations done on an ATV vehicle (F n table 2 and 3):

9.1.1 Equivalent field test (case a)

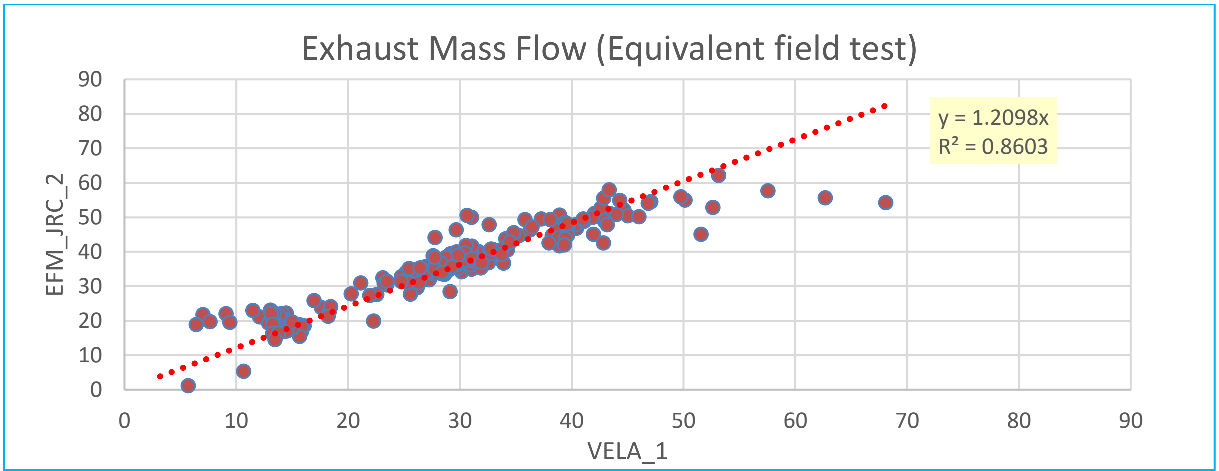
In this case, we reproduced in the reference chassis dyno test bench a part of a real test performed in the field ("equivalent field" test). See Figures 28 and 29.

Figure 28. Exhaust Mass Flow - Vela 1 vs EFM_JRC_2 ("equivalent field" test).



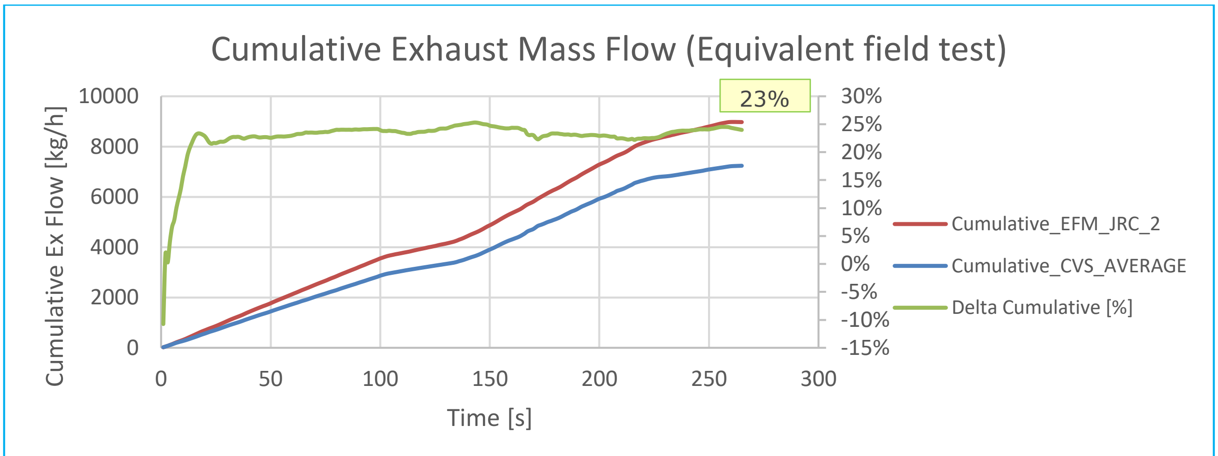
Source: JRC.Vela, 2019

Figure 29. Exhaust Mass Flow - Linear correlation between Vela 1 and EFM_JRC_2 ("equivalent field" test).



The stabilized delta of the two cumulative data series is around 23% (see Figure 30)

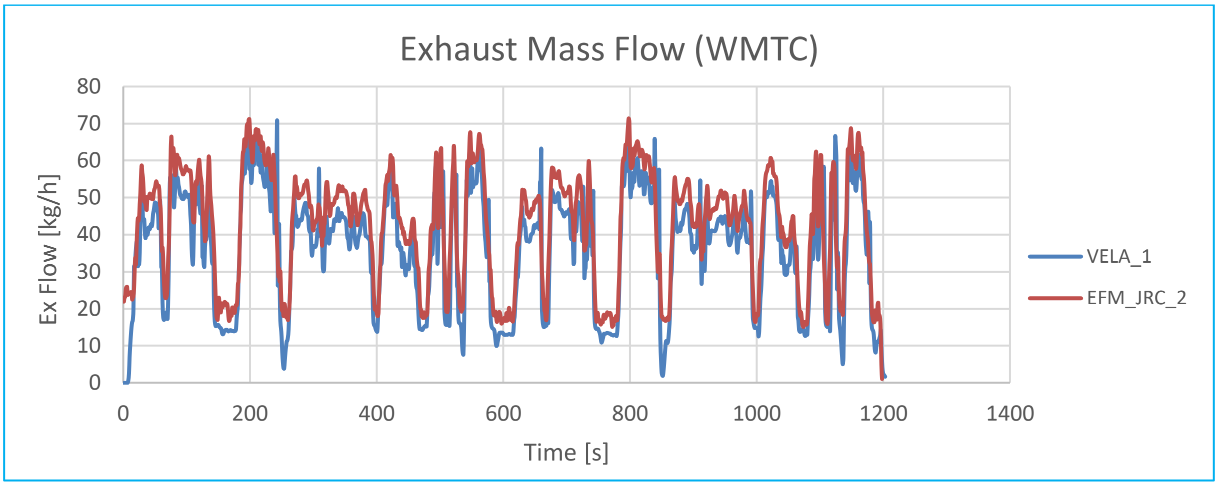
Figure 30. Exhaust Mass Flow cumulated data EFM_JRC_2 vs VELA_1 CVS ("equivalent field" Test).



9.1.2 Regulatory transient test cycle (WMTC) (case b)

In this case, a regulatory transient test cycle (WMTC) is run in the reference chassis dyno test bench. See Figures 31 and 32.

Figure 31. Exhaust Mass Flow - Vela 1 vs EFM_JRC_2 (WMTC test).



Source: JRC.Vela, 2019

Figure 32. Exhaust Mass Flow - Linear correlation between Vela 1 and EFM_JRC_2 (WMTC test).

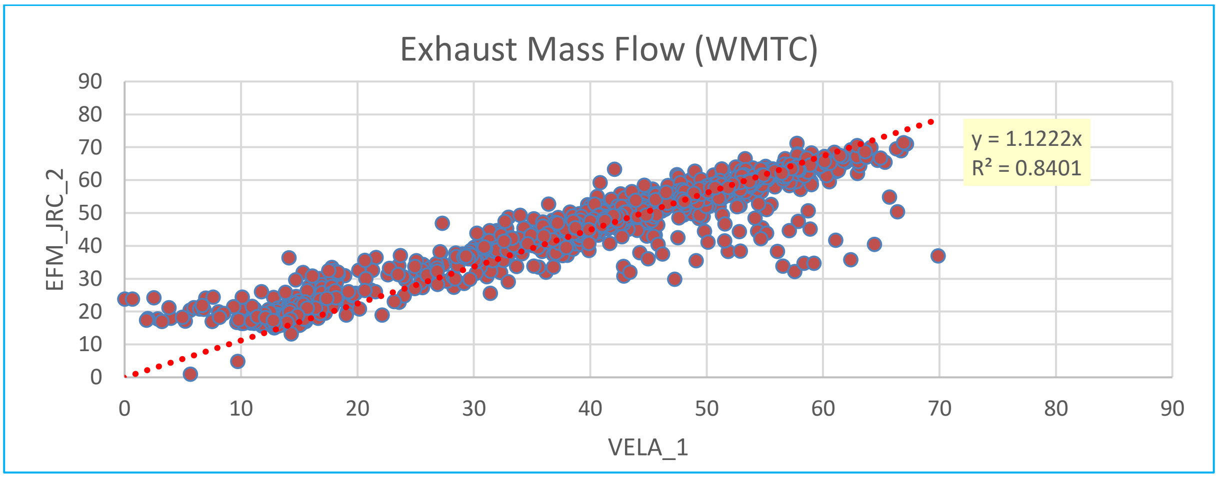
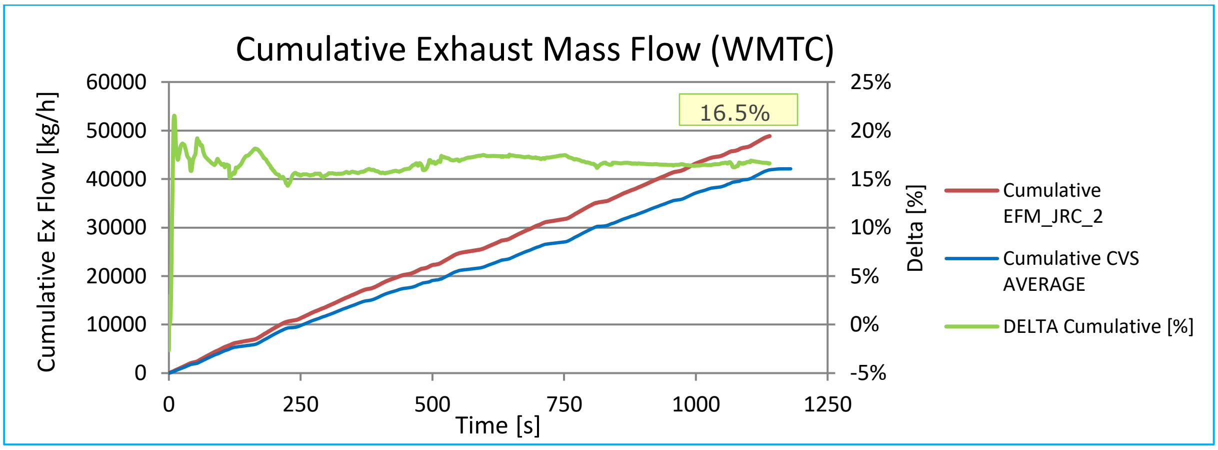


Figure 33. Ex Mass Flow cumulated data EFM_JRC_2 vs VELA_1 CVS (WMTC Test).



The stabilized delta of the two cumulative data series is around 16.5% (see Figure 33).

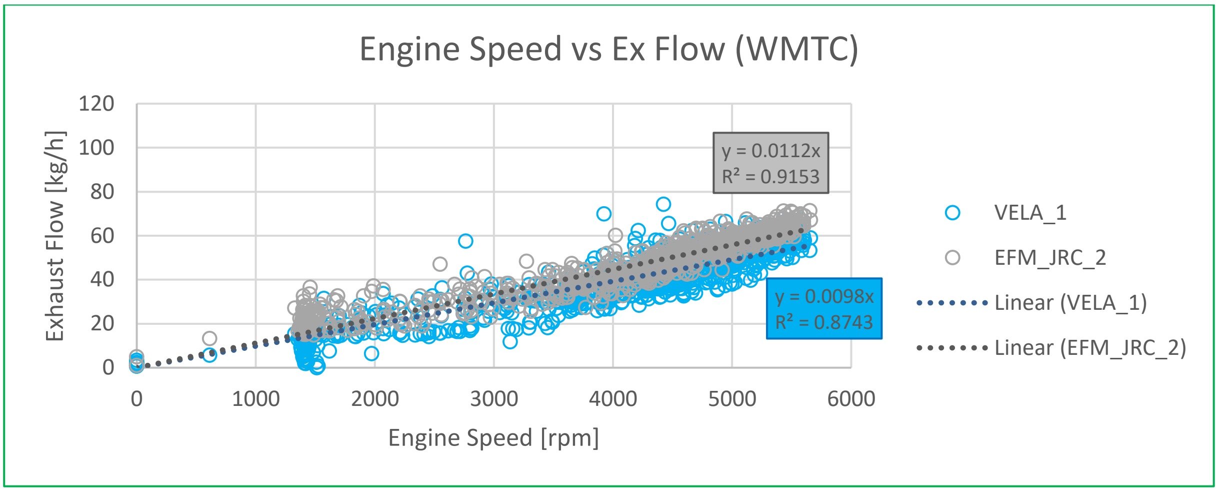
9.1.3 Indirect comparison of both exhaust flow meters (EFM_JRC_1 and EFM_JRC_2)

We have analysed the variation of the exhaust mass flow with the engine speed for both instruments.

The exhaust flow readings obtained using EFM_JRC_2 are in good agreement with the value measured by the CVS in both tests; i.e. WMTC and equivalent field test (see Figure 34 and 35). Therefore, the EFM_ JRC_2 can be considered as a reliable instrument for exhaust flow measurements.

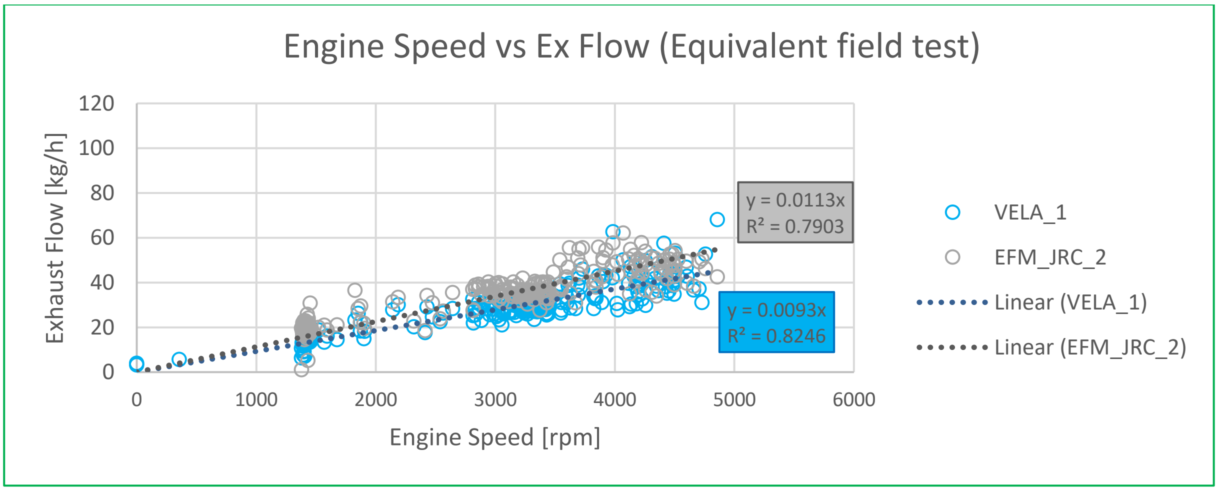
The comparison between EFM_JRC_1 and EFM_JRC_2 (see Figure 36 and 37) indicates that an offset factor taking into account the measuring difference could be applied.

Figure 34. Engine speed vs Exhaust Mass Flow – Comparison between CVS VELA_1 and EFM_JRC_2 (WMTC Test).



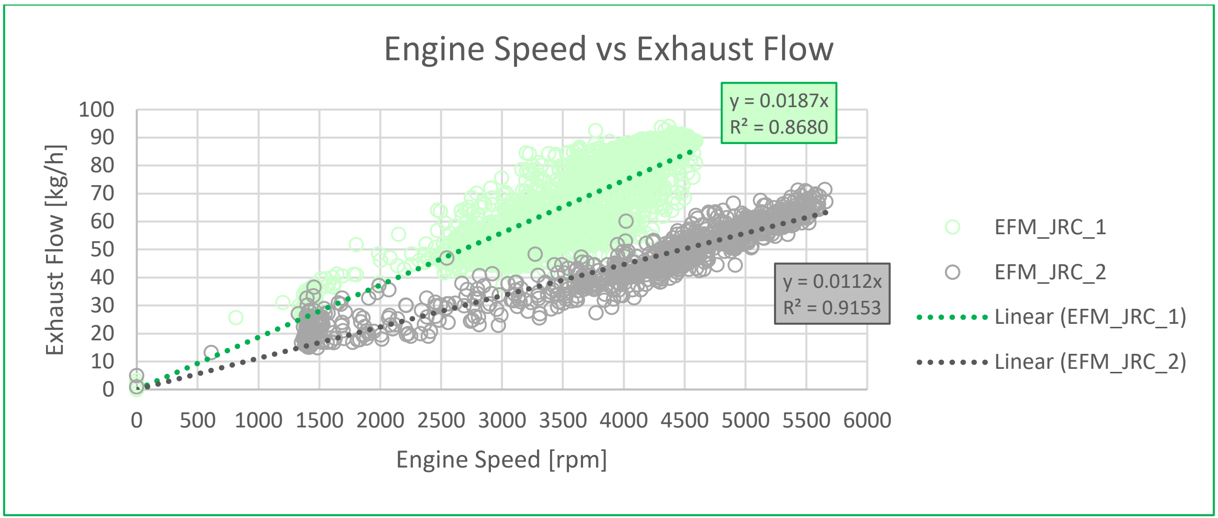
Source: JRC.Vela, 2019

Figure 35. Engine speed vs Exhaust Mass Flow – Comparison between CVS VELA_1 and EFM_JRC_2 (“Equivalent field” Test).



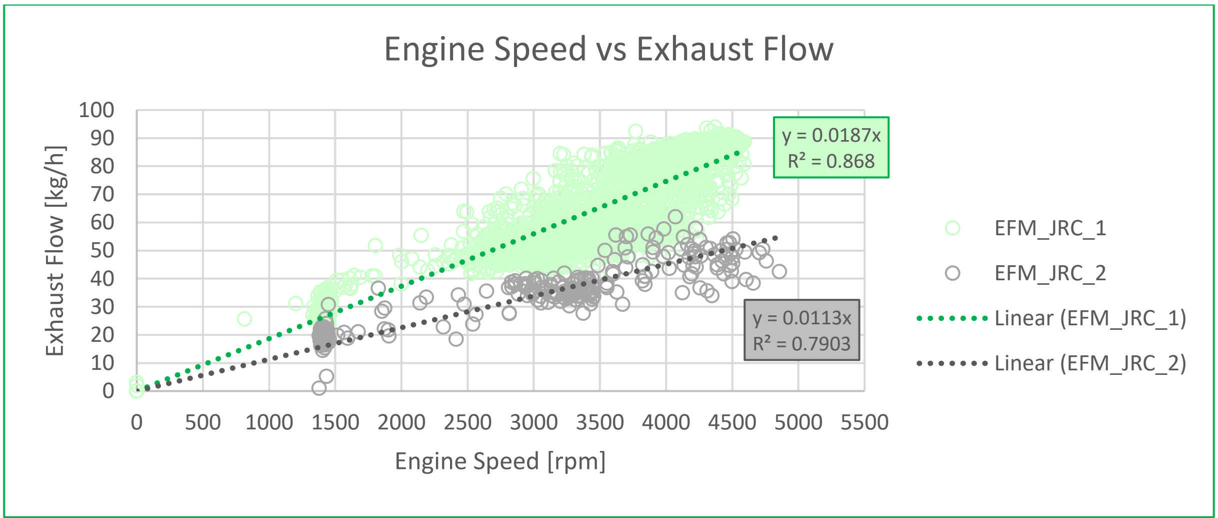
Source: JRC.Vela, 2019

Figure 36. Engine speed vs Exhaust Mass Flow – Comparison between EFM_JRC_1 and EFM_JRC_2 (WMTC Test).



Source: JRC.Vela, 2019

Figure 37. Engine speed vs Ex Mass Flow – Comparison between EFM_JRC_1 and EFM_JRC_2 (“Equivalent field” Test).

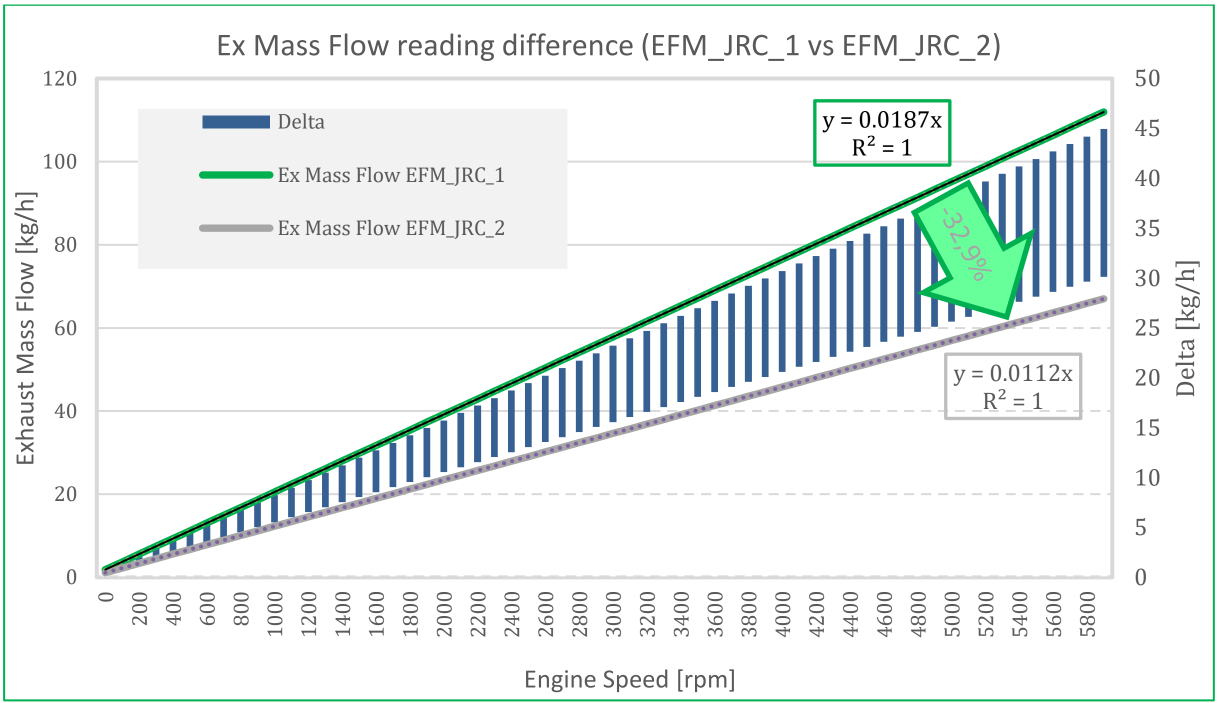


Source: JRC.Vela, 2019

9.1.4 Correction to the exhaust mass flow

Since we can consider the exhaust mass flow directly proportional to the engine speed, using the above graphs, we can calculate the expected exhaust flow values in function of the engine speed. If we plot the values corresponding to the two mass flows in a common graph, we can gather the equation of the trend line and in particular the slope of the best-fit line for each EFM; i.e. EFM_JRC_1 and EFM_JRC_2 (see Figure 38).

Figure 38. Exhaust Mass Flow reading difference.



Source: JRC.Vela, 2019

Now we can calculate the difference between the reading capabilities of the two flowmeters used, as it follows:

{1-[(0.018657-0.011168)/0.011168]}*100= 32,9%

which will be assumed as a constant in all the engine speed range.

So, where we have used the EFM_JRC_1, we can apply a correction of a -32,9% in all the engine speed range, to have values in line with the reading capability of EFM_JRC_2

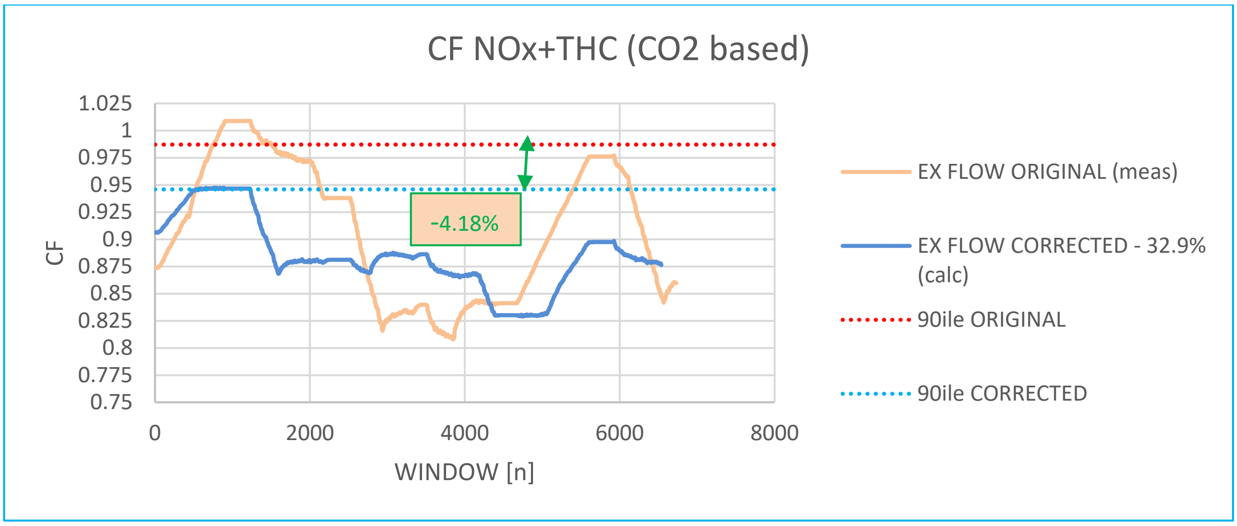
Recalculating the CFs using the corrected flow, we detected a difference in CF final value that, in the worst case, is limited to 10% of error. The investigation has been made using the CO2 WORK BASED Moving Average Windows (CO2MAW) approach (see Table 11).

Table 11. Difference evaluation in CFs (NOX+THC and CO) using the proposed correction.

CF NOx+THC (DELTA)	CF CO (DELTA)
-4.18%	-10.14%

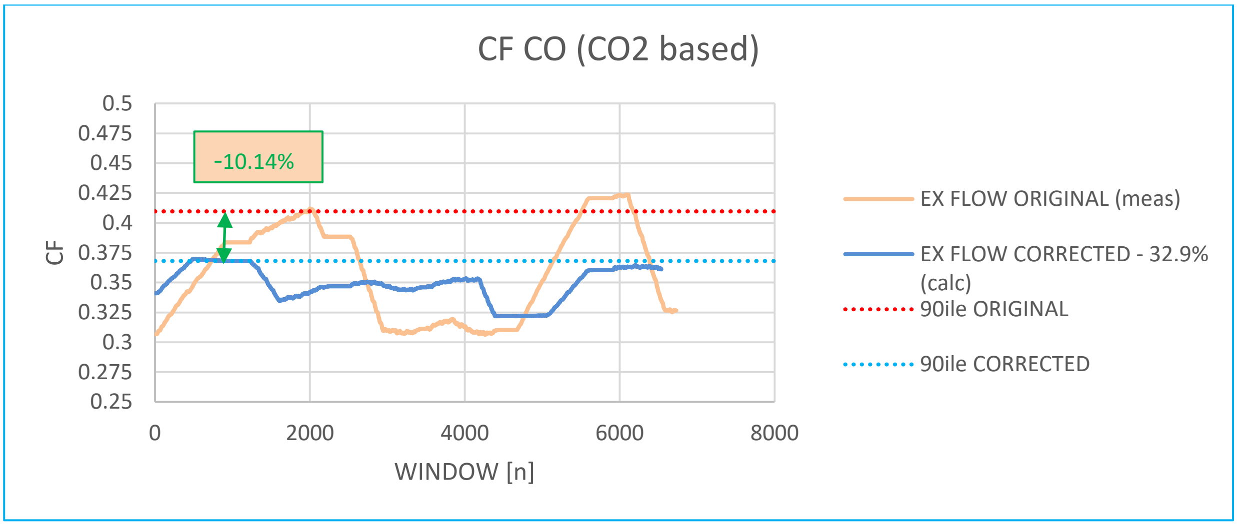
In the above analysis all the data has been used, without any exclusion (cold start, working/not working events, etc).

Figure 39. NOX+THC CF – 90th percentile values (Original vs Corrected dataset).



Source: JRC.Vela, 2019

Figure 40. CO CF – 90th percentile values (Original vs Corrected dataset).



Source: JRC.Vela, 2019

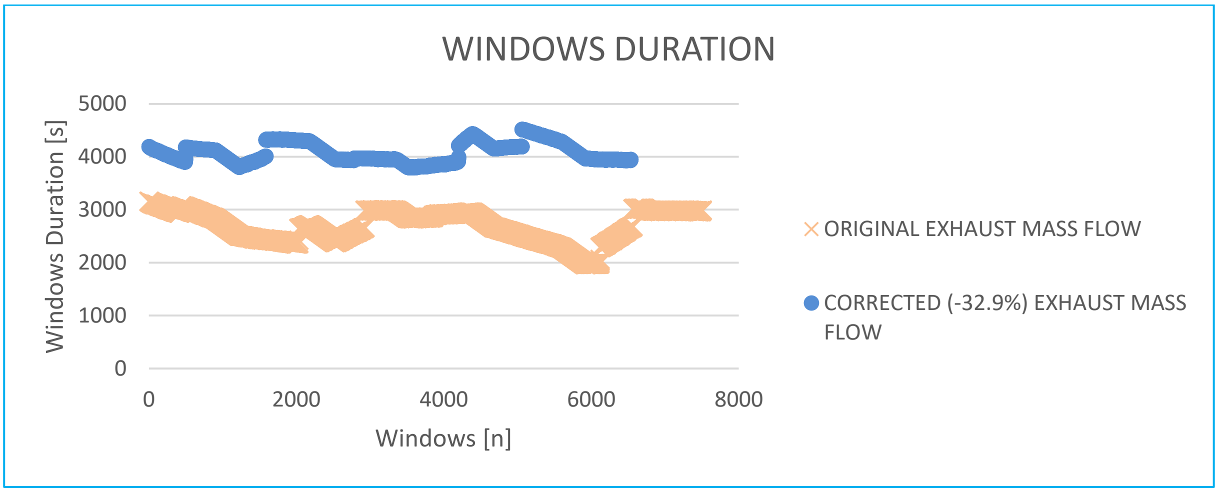
In average applying the proposed correction, we obtain CF values for each window lower than the original data (without the correction) and this is valid as a trend (see Figures 39 and 40). It is worthwhile to notice that, in some limited cases, this trend seems to be opposite. The reason being in the different duration of the window in both cases (see Figure 41). The length of the windows calculated for the corrected case, is in average longer than in the original case (see Table 12).

Table 12. Average windows duration (Original data set vs Corrected data set).

	Average Windows Duration [s]
Original test	2689.68
Corrected test	4084.26

Source: JRC.Vela, 2019

Figure 41. Instantaneous windows duration (in seconds). All windows have been depicted (valid and invalid).



Source: JRC.Vela, 2019

In some windows, the amount of pollutant contained in the window (relative to CO_2 amount in grams) of the corrected test, could result higher than the one in the original windows. For detail refers to Figures 42 and 43, in which are represented the pollutants data in grams per kilograms of CO2 produced (reference value).

Figure 42. Instantaneous NOX+THC content window by window (in g/kg CO2).

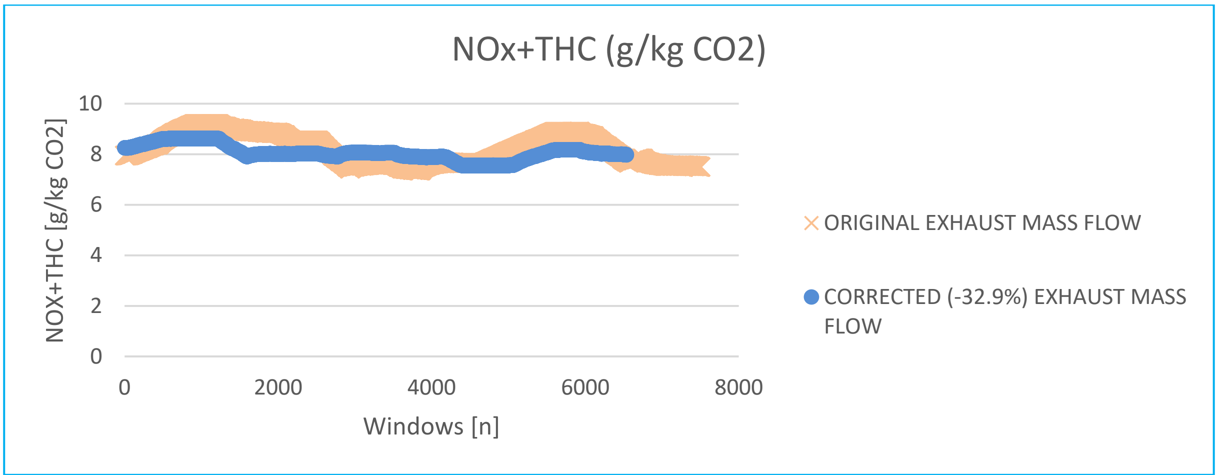
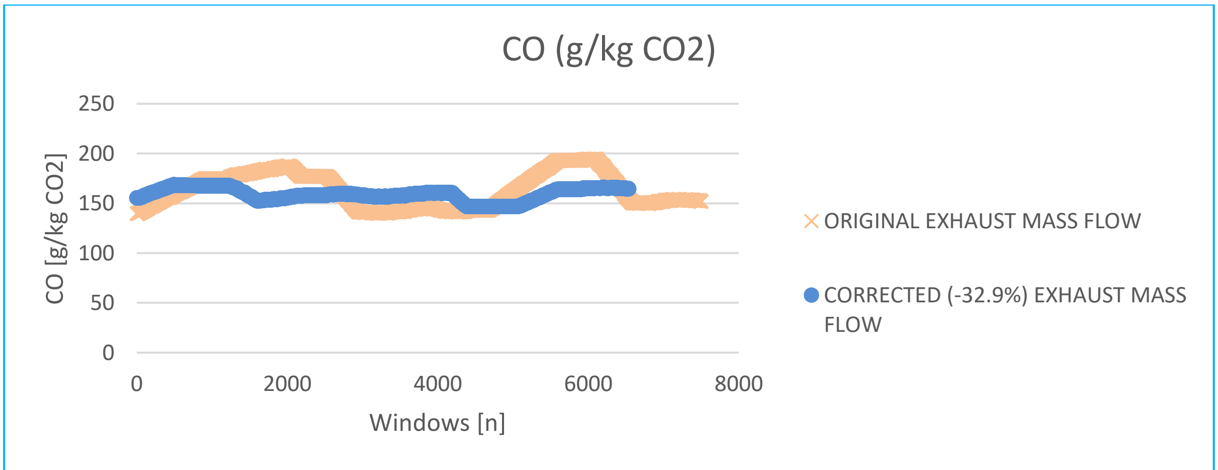


Figure 43. Instantaneous CO content window by window (in g/kg CO2).



To summarize, we detected that an error of more than 30% in the mass flow reading, have an impact in the final CF calculation that is limited to 10% in the worst case (CO). This is explainable because the final CF assigned to the test is the 90th percentile, in which the maximum values (peaks) are not considered because they are on the top 10th percentile.

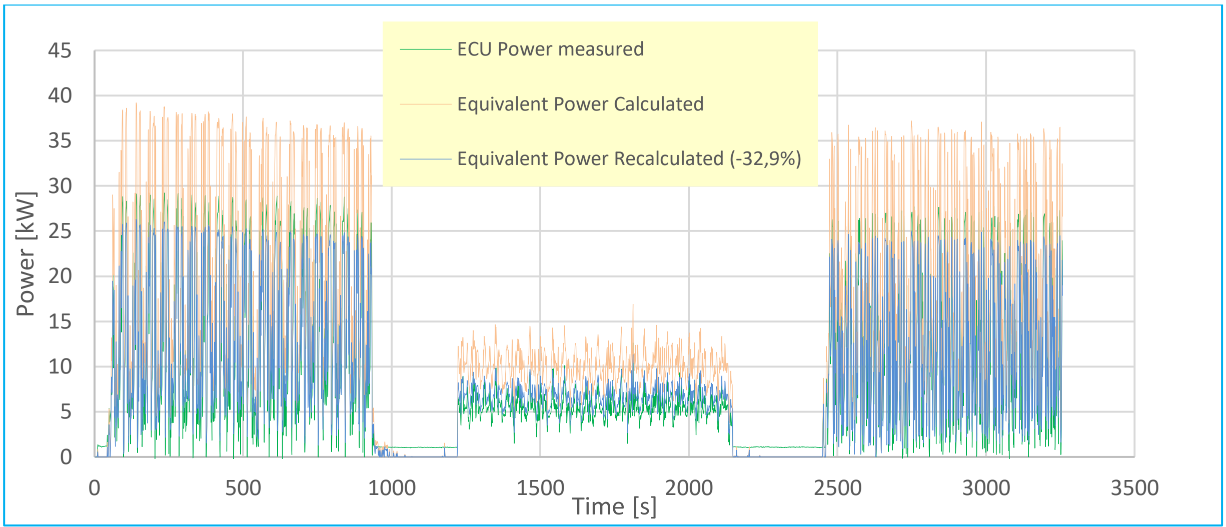
If we apply the mass flow correction above presented to the "Veline" procedure to calculated the equivalent power, we find that the values of the power measured by the ECU and the equivalent ones calculated using the CO_2 method are much closer, giving us a certain confidence in the application of the discussed correction.

With reference to the following ATV case, we can see that the instant equivalent power calculated using the corrected exhaust mass flow (see Figure 44 in blue) is in very good agreement with the power obtained from the ECU.

This example refers to a NRMM ATV machine/vehicle equipped with an engine whose maximum power was limited at 39.6 kW at 5000 rpm that has undergone an in-service (IS) test using PEMS. Its NRSC reference work is 9.263 kWh and its reference CO_2 is 8139 g. Hence, the CO_2 values presented are obtained from on-board PEMS measurements.

K can be calculated from the above type approval values for this engine: **K=878.66 g/kWh.**

Figure 44. Plot showing power measured by the ECU and the equivalent power calculated based on the "Veline" approach (original data and exhaust mass flow corrected).



Source: JRC.Vela, 2019

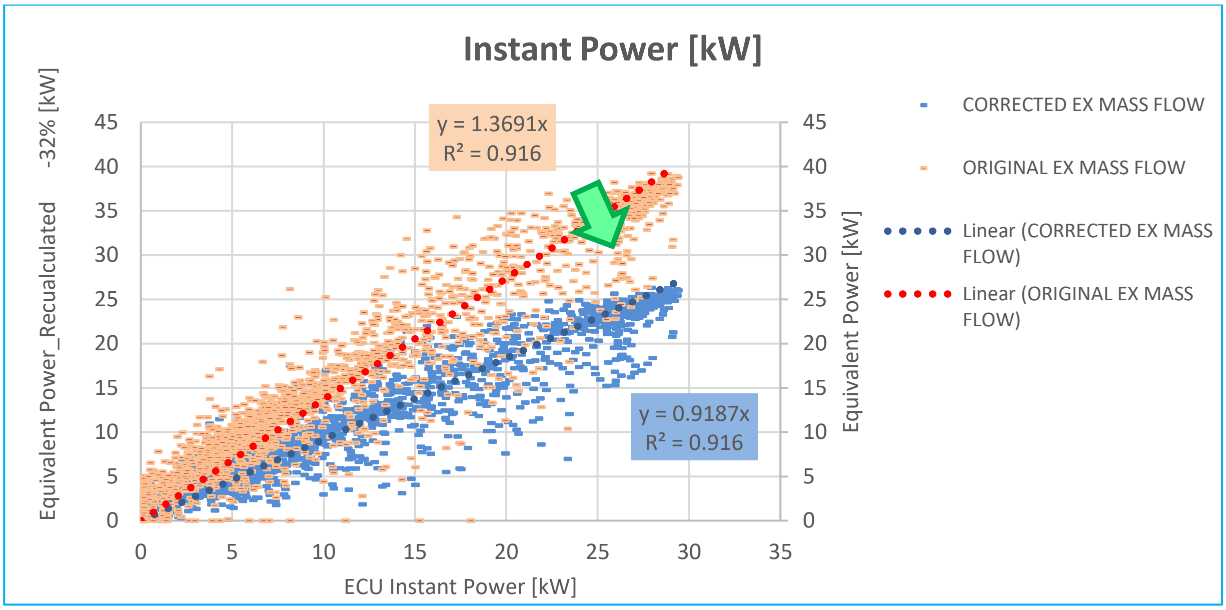
As usual, the power has been calculated using the following formula:

$$P_i = \frac{CO_{2_i}}{K_{NRTC}}$$ and considering the CO_2 flow is measured in g/s, then:

$$P_i = \frac{CO_{2_i}}{878.68} \cdot 3600 \; [kW]$$

If we plot the instant power form the ECU versus the instant equivalent power calculated with the "Veline" approach (with and without exhaust mass flow correction) and check for linearity, it can be seen that for obvious reasons, both cases have the same coefficient of determination R^2 of 0.919 which indicates a strong correlation. However, while the calculation without correction has a deviation (represented by the angular coefficient) of around 37%, the deviation falls down until -8% when applying the above mentioned correction. (Please refer to Figure 45).

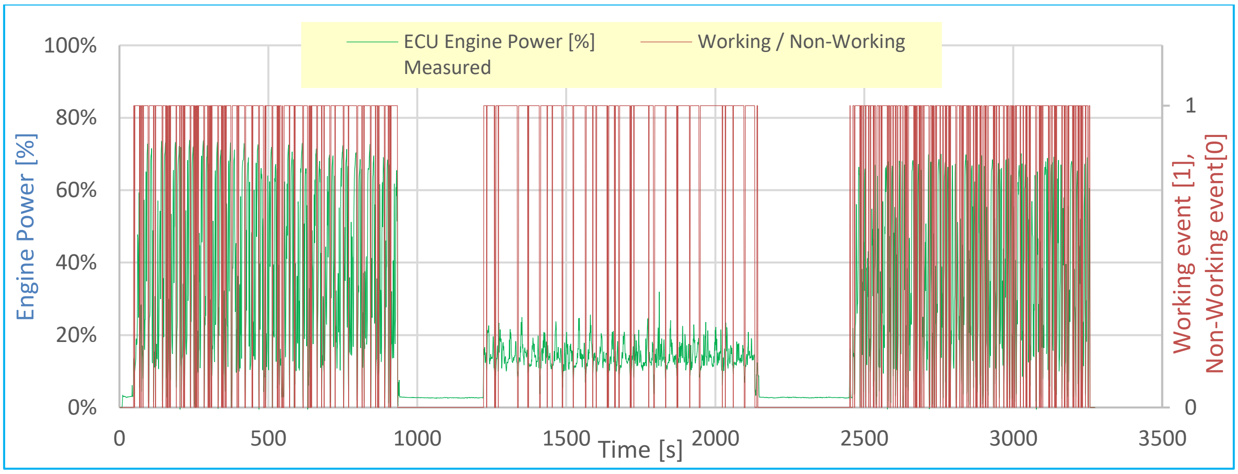
Figure 45. Linear least square showing the relation between instant power and CO2 flow in the 2 cases: orange without exhaust flow correction; blue with correction.



Source: JRC.Vela, 2019

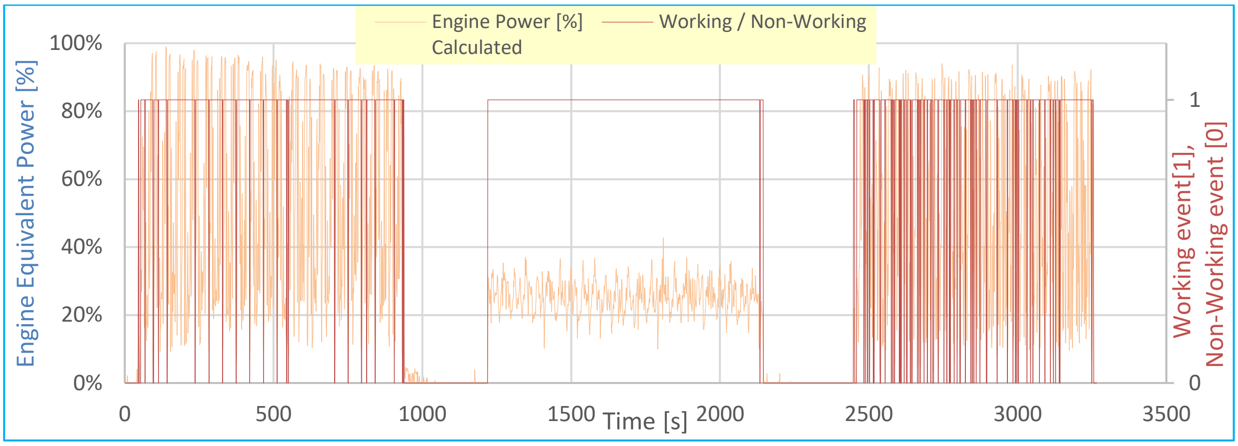
The effect on the working/non-working event definition (P > 10% P_{max}) for the case studied using the measured power, and the equivalent calculated power for the original measured exhaust flow and the corrected flow is illustrated in Figure 46, Figure 47 and Figure 48 respectively. For all calculations, the cold start emissions were not excluded.

Figure 46. Working/Non-Working events using the measured power (ECU).



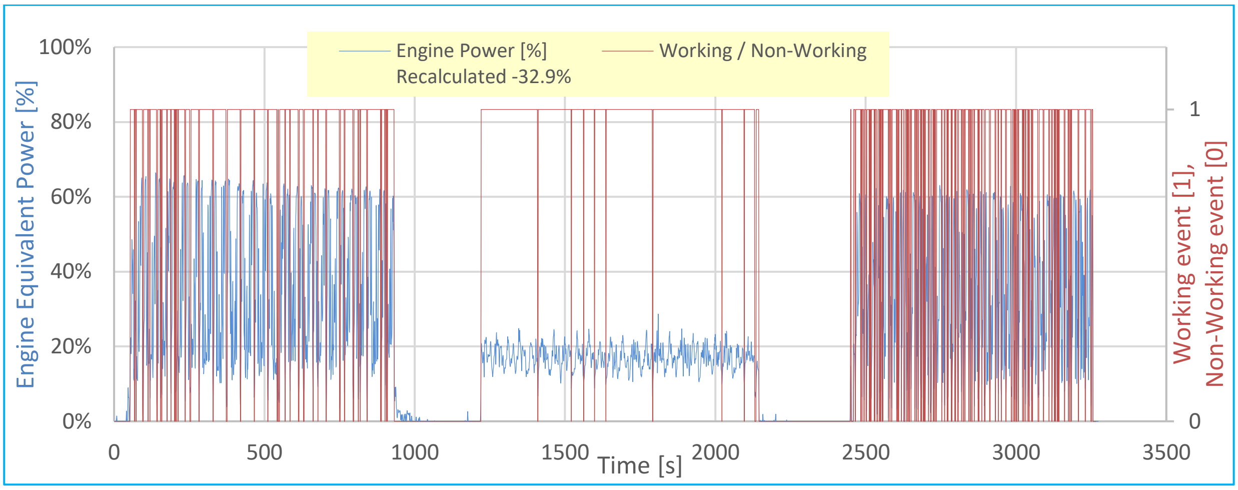
Source: JRC.Vela, 2019

Figure 47. Working/Non-Working events using equivalent engine power (calculated) – Original data set.



Source: JRC.Vela, 2019

Figure 48. Working/Non-Working events using equivalent engine power (calculated) – Corrected data set.



Source: JRC.Vela, 2019

The main purpose of this methodology is the selection of working and not working events for the case where the CO2MAW is used as emission determination procedure. Therefore, it is important to compare the number of events below 10% of the maximum net power of this engine for the case of power being measured (torque x rpm obtained from the ECU) and for that of the calculated equivalent power using the proposed methodology for both corrected and not corrected data set (see Table 13).

Table 13. Difference between the power "measured" by the ECU, the original and corrected power calculated using the "Veline" approach (P<10% Pmax excluded).

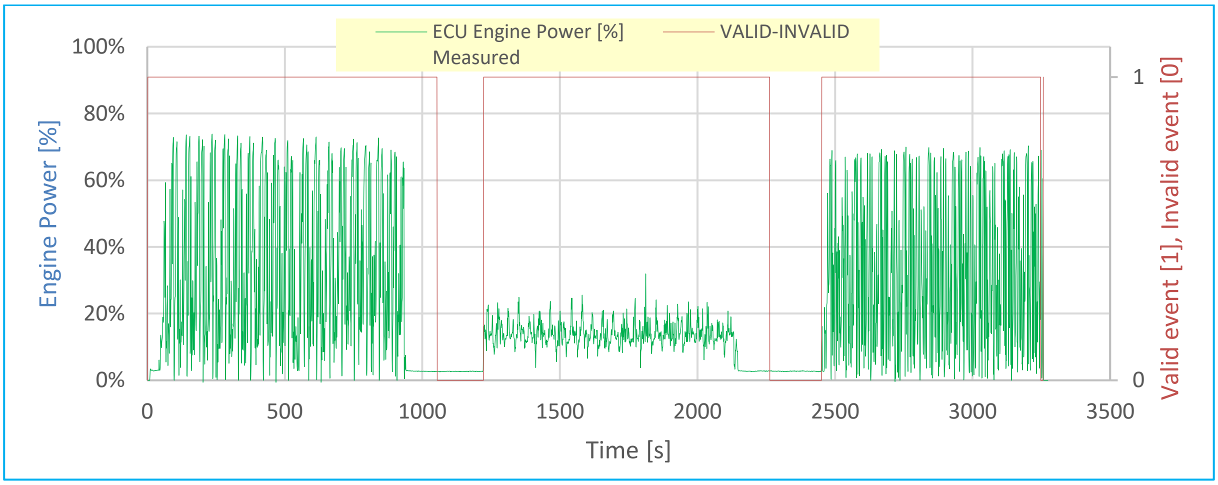
EXCLUSION: BASELINE (P <10% Pmax)	**ECU MEASURED**	**CALCULATED original flow**	**CALCULATED corrected flow (-32.9%)**
Total Number of events	3257	3257	3257
Number of events with P<10% Pmax	995	756	860
% of non-working events	**30.55%**	**23.21%**	**26.40%**

Source: JRC.Vela, 2019

In the above evaluation, the NON-WORKING parameters (D0-D1-D2-D3) are not considered. If we considered also these parameters and using the “Veline” approach, the valid-invalid area designed by the ECU power and the equivalent power calculated starting from CO_2 are practically coincident; in fact, we can identify the same valid/invalid areas.

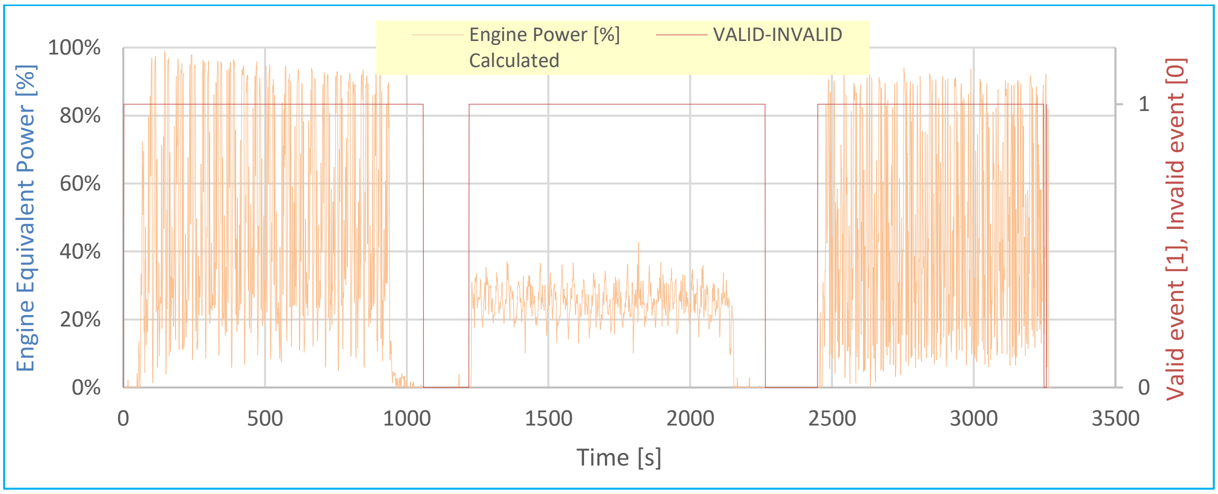
As shown in Figures 49, 50 and 51 and Table 14, it is also important to find out whether the calculated equivalent power from the CO_2 will provide the same data distribution as in the case of the measured power once the procedure to determine valid/invalid events is applied.

Figure 49. Valid/invalid events using the measured power (ECU).



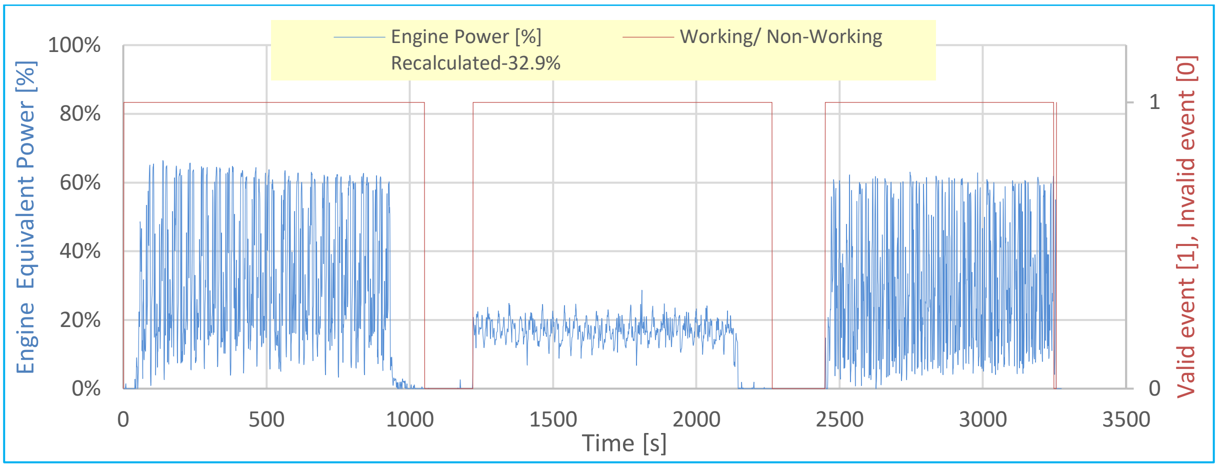
Source: JRC.Vela, 2019

Figure 50. Valid/invalid events using equivalent engine power (calculated) – Original data set.



Source: JRC.Vela, 2019

Figure 51. Valid/invalid events using equivalent engine power (calculated) – Corrected data set.



Source: JRC.Vela, 2019

Table 14. Comparison of the number and percentage of invalid events by using the power "measured" by the ECU, the original and corrected (EFM) equivalent power calculated by using the "Veline" approach.

EXCLUSION: BASELINE (P<10% Pmax) + WORKING/NOT WORKING EVENTS (D0/D1/D2/D3)	**ECU MEASURED**	**CALCULATED original flow**	**CALCULATED corrected flow (-32.9%)**
Total Number of events	3257	3257	3257
Number of invalid events	368	356	364
% of invalid events	**11.30%**	**10.93%**	**11.18%**

Source: JRC.Vela, 2019

10 Conclusions and recommendations

This report has presented the outcome of the pilot programme designed to explore the suitability of the already existing procedure to monitor the gaseous pollutant emissions[12] for its application to test in-service (ISM) internal combustion engines installed in NRMM category ATS. The report confirms that for ISM tests, the use of Portable Emission Measurement Systems (PEMS) is suitable as it can be reliably mounted on the tested machine and the data can also be processed in a similar fashion as in the case for NRMM engines of category NRE-v-5 and NRE-v-6[12].

Because of the characteristics of ATS NRMM (i.e. this category of engines tend to be single- or 2-cylinders) the measurement of the exhaust mass flow using flow meters (EFM) has turned to be more complicated than expected due to the exhaust flow pulsation typical of this kind of engines. This was an important point because although the precision and accuracy of the concentration of gaseous pollutants using PEMS has been proven once again, the instant mass of those pollutants are governed by the uncertainty of the EFM.

Technical solutions have been found for both the installation of PEMS on board of NRMM ATS machinery and the measurement of the exhaust flow with an acceptable uncertainty. To that extend the following recommendations are made:

1. To measure and record the Exhaust Mass Emission in kg/h at high measurement rate. The use of high-speed sampling by the EFM allows for the correct measurement of the reverse flow for pulsating engines. Some commercially EFM are available from PEMS manufacturers

2. Commercially available PEMS are suitable for using in the ISM test on the field, although appropriate mounting and protecting solutions need to be found. This report provides some hints to that extend.

3. The ISM test can be carried out by following the normal/usual operations that the NRMM ATS undergoes in the field.

During the performance of the pilot programme solutions were found for the definition of the reference quantities; i.e. work and CO_2 for the case that the type approval test is the NRSC rather than the NRTC. It has also been proposed a methodology to calculate an equivalent power from the measured CO_2 flow in order to make possible the definition of working and non-working event for the case of mechanically controlled engines (no ECU). The validation of this approach suggests that the approach is suitable for the purpose to define valid/invalid events.

Due to the power range of these NRMM engines and the long time necessary to complete 5 to 7 times the reference values (i.e. work or CO_2 at type approval) the reduction of the length of the test to complete 3 to 5 times the reference values is recommended.

Furthermore, regarding the data sampling method and without prejudice of the reduction of the length of the test indicated in the above paragraph the use of combined data sampling following paragraph 4 of the Annex to Reg. (EU) 2017/655 with appropriate adjustments should be allowed. This will reduce the possible burden to the testing team and OEM during the ISM tests.

A suitable plan for monitoring ATS in-service engines needs to be developed together with the industrial association (ATVEA) which needs to include appropriate schemes to provide data at different points in the life of the in-service ATS engine similar to that developed for category NRE-v-5 and NRE-v-6[12].

[12] Reg. (EU) 2017/655

List of abbreviations and definitions

ATS	All Terrain Vehicle and Side-by-Side
ATV	All Terrain Vehicle
ATVEA	All Terrain Vehicle Industry European Association
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2AW	CO_2 based Average Window
DG GROWTH	Directorate General Internal Market, Industry, Entrepreneurship and SMEs
EC	European Commission
EFI	Electronic Fuel Injection
EFM	Exhaust Flow Meter
EU	European Union
ISM	In-Service Monitoring (Programme)
JRC	Joint Research Centre
MAW	Moving Average Window
NOx	Oxides of Nitrogen
NRMM	Non Road Mobile Machinery
OEMs	Original Equipment Manufacturer
PEMS	Portable Emission Measurement System
SMEs	Small and Medium Enterprises
SOHC	Single OverHead Camshaft
SxS/SbS	Side by Side
THC	Total HydroCarbons, also referred to as HC
TWC	Three-Way Catalyst
VELA	Vehicle Emission LAboratory
WAW	Work based Average Window

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Annexes

Annex 1. Stage V emission limits by engine category

Table 15. Stage V emission limits.

Stage V emission limits by engine category

Engine Category	Equipment Type	Power Range (kW)	Engine Type	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)	PN (#/kWh)	A#
NRE-v-1 NRE-c-1	Other non-road mobile machinery	0<P<8	CI	8.00	HC+NOx≤7.50		0.40	-	1.1
NRE-v-2 NRE-c-2		8≤P<19	CI	6.60	HC+NOx≤7.50		0.40	-	1.1
NRE-v-3 NRE-c-3		19≤P<37	CI	5.00	HC+NOx≤4.70		0.015	$1x10^{12}$	1.1
NRE-v-4 NRE-c-4		37≤P<56	CI	5.00	HC+NOx≤4.70		0.015	$1x10^{12}$	1.1
NRE-v-5 NRE-c-5		56≤P<130	All	5.00	0.19	0.40	0.015	$1x10^{12}$	1.1
NRE-v-6 NRE-c-6		130≤P≤560	All	3.50	0.19	0.40	0.015	$1x10^{12}$	1.1
NRE-v-7 NRE-c-7		P>560	All	3.50	0.19	3.50	0.045	-	6.0
NRG-v-1 NRG-c-1	Generating sets	P>560	All	3.50	0.19	3.50	0.045	-	6.0
NRSh-v-1a	Equipment with SI engines	0<P<19	SI	805	HC+NOx≤50		-	-	-
NRSh-v-1b		0<P<19	SI	603	HC+NOx≤72		-	-	-
NRS-vr-1a NRS-vi-1a		0<P<19	SI	610	HC+NOx≤10		-	-	-
NRS-vr-1b NRS-vi-1b		0<P<19	SI	610	HC+NOx≤8.00		-	-	-
NRS-v-2a		19≤P<30	SI	610	HC+NOx≤8.00		-	-	-
NRS-v-2b NRS-v-3		19≤P≤56	SI	4.40•	HC+NOx≤2.70•		-	-	-
IWP-v-1 IWP-c-1	Inland waterway vessels	37≤P<75	All	5.00	HC+NOx≤4.70		0.30	-	6.00
IWP-v-2 IWP-c-2		75≤P<130	All	5.00	HC+NOx≤4.70		0.14	-	6.00
IWP-v-3 IWP-c-3		130≤P<300	All	3.50	1.00	2.10	0.11	-	6.0
IWP-v-4 IWP-c-4		300≤P≤1000	All	3.50	0.19	1.20	0.22	$1x10^{12}$	6.0
IWP-v-5 IWP-c-4		P>1000	All	3.50	0.19	0.40	0.01	$1x10^{12}$	6.0
IWA-v-1 IWP-c-a		560≤P<1000	All	3.50	0.19	1.20	0.02	$1x10^{12}$	6.0
IWA-v-2 IWA-c-2		P≥1000	All	3.50	0.19	0.40	0.01	$1x10^{12}$	6.0
RLL-c-1 RLL-v-1	Railway	P>0	All	3.50	HC+NOx≤4.000		0.025	-	6.00
RLR-c-1 RLR-v-1		P>0	All	3.50	0.19	2.00	0.015	$1x10^{12}$	6.0
SMB-v-1	Snowmobilies	P>0	SI	75	-	-	-	-	-
ATS-v-1	AVs and SbS	P>0	SI	400	HC+NOx≤8.00		-	-	-

# •	Where in "A" factor is defined, the HC emission limits for fully and partially gaseous fueled engines will be calculated with the following formula: HC= 019 + (1.5 X A X GER), where the gas energy ration (GER) is the average gas energy ratio over the appropriate cycle. The average GER is determined by the hot-start transient test cycle in both the non-road steady cycle (NRSC) AND THE TRANSIENT CYCLE (NRTC). If calculated NH limits exceed the value of 0,19 + A, the limits should be set to 0,19 + A. Alternatevely, any combination of satysfying the equation (HC+NOx)•CO ^0,784 ≤ 8.57, as well as the following conditions: CO 20.6 g/kWh and (HC+NOx) ≤ 2.7 g/kWh
CI	Compression-ignition engines (also known as diesel engine)
SI	Spark-ignition engines (also known as internal combustion engines, or petrol engines)

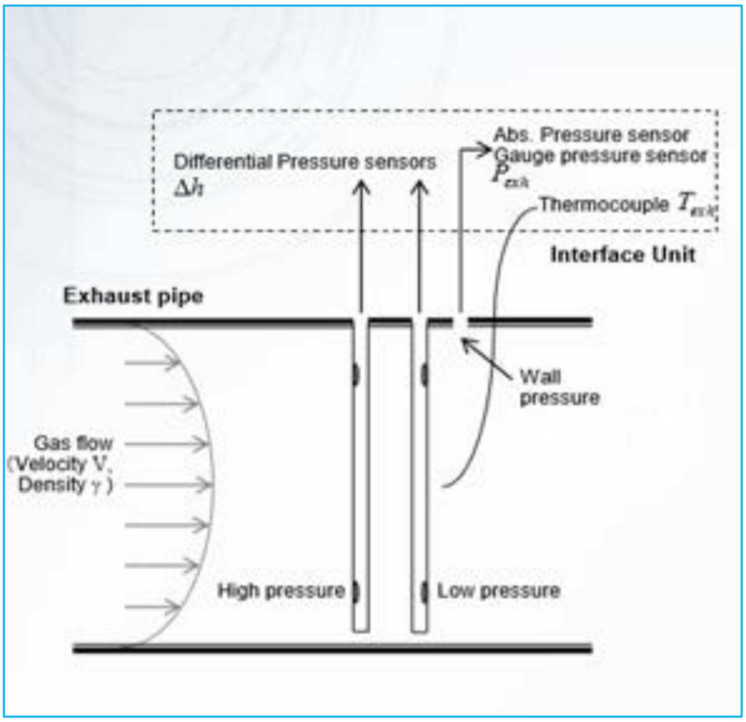
Source: JRC.Vela, 2017

Annex 2. Pitot tube flowmetering technique – Error with high pulsation (Literature case)

The Pitot tube flowmetering technique (see Figure 52) has been used to measure pulsating flow from a machine/vehicle engine exhaust. In general, flowmetering techniques that utilize differential pressure measurements based on Bernoulli's theory are likely to show erroneous readings when measuring an average flowrate of pulsating flow. The primary reason for this is the non-linear relationship between the differential pressure and the flowrate; i.e. the flowrate is proportional to the square root of the differential pressure. Therefore, an average of the differential pressure does not give an average of pulsating flow, unless fast response pressure transducers are used to measure the pulsating pressure. Then the pulsating differential pressure is converted to the flowrate while the pulsation is not averaged. An average flowrate is then calculated in the flowrate domain in order to maintain linearity before and after averaging. The results normally show a large amount of back and forth gas movement in the exhaust tube. This magnitude of pulsation can cause as much as five times higher erroneous results with the pressure domain averaging when compared to a flowrate domain averaging.

Here below is presented a literature case supplied by Horiba[13], in which a high speed logging instruments was not used. As it shown below, the risk to overestimate the flow is concrete, as it is an average measure.

Figure 52. Pitot working principle.

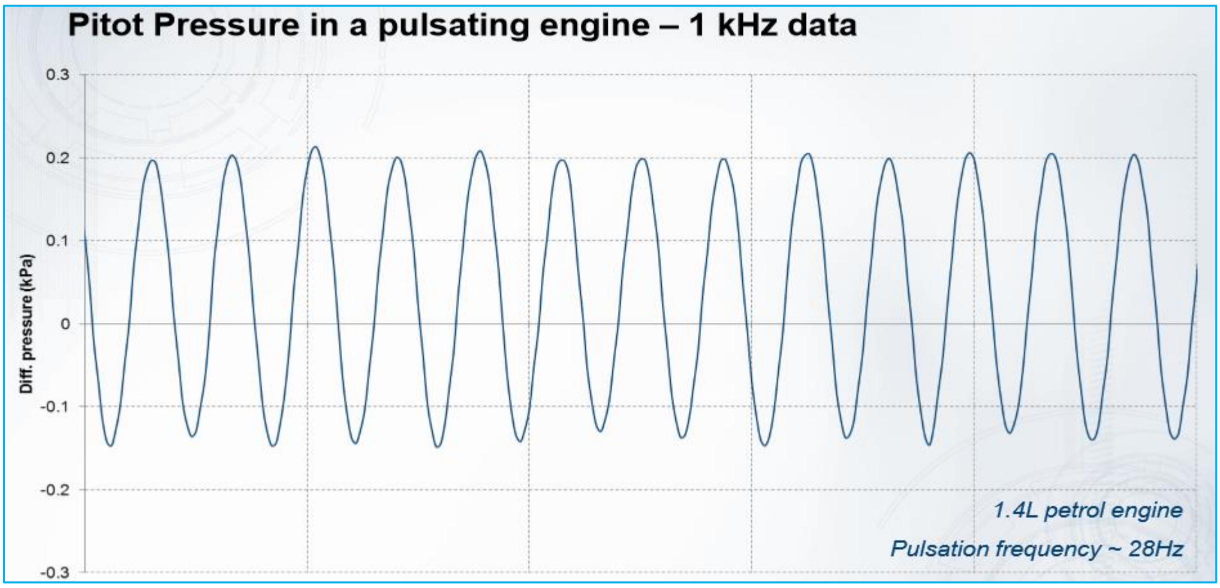


Source: Horiba, 2013

The case study, show a 1.4 liter petrol engine, with a pulsation frequency around 28 Hz (see Figure 53).

[13] Exhaust Flow Metering Nov 2013 HORIBA

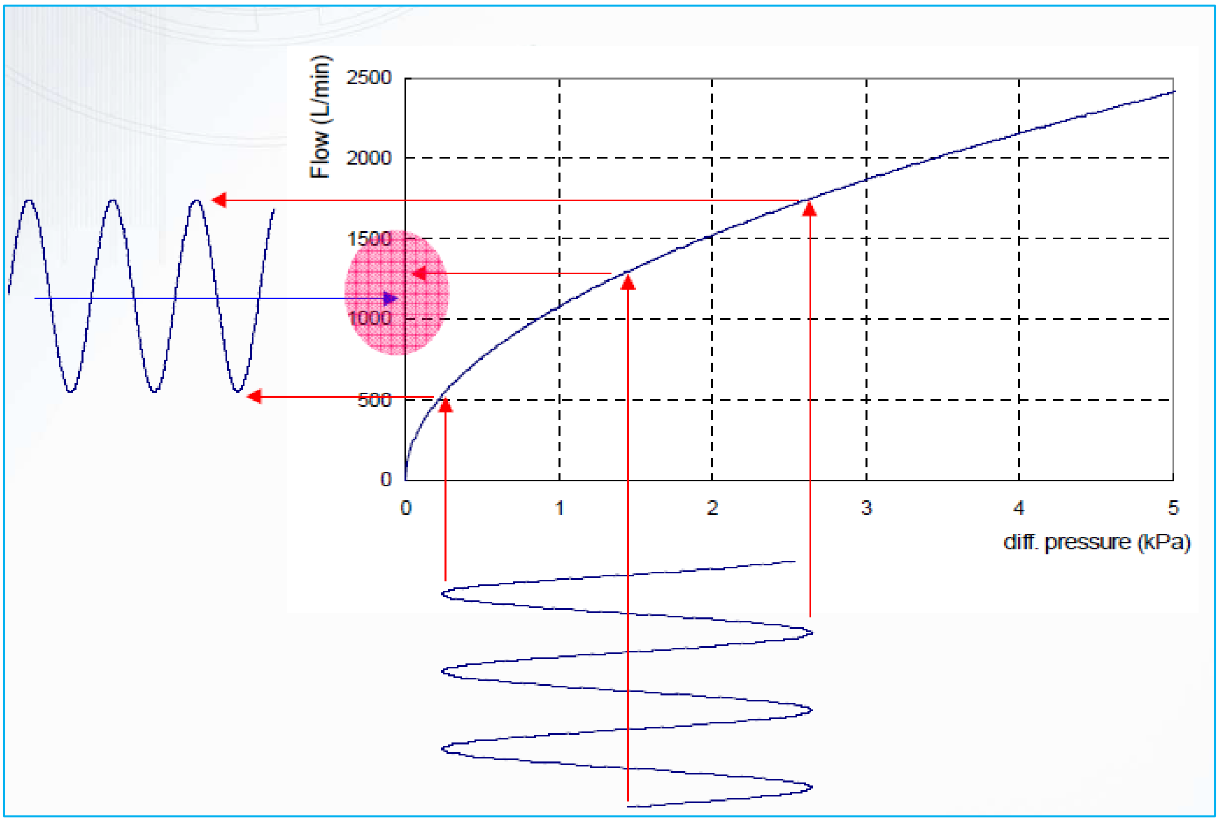
Figure 53. Differential pressure signal in the Pitot in our study case.



Source: Horiba, 2013

This is due to an error in the Root Mean Squared error. According to Horiba and others, an average of pulsation in the differential pressure dimension is different from the average in the flow dimension, owing to the non linear signal, as shown in the figures below (Figure 54-55-56).

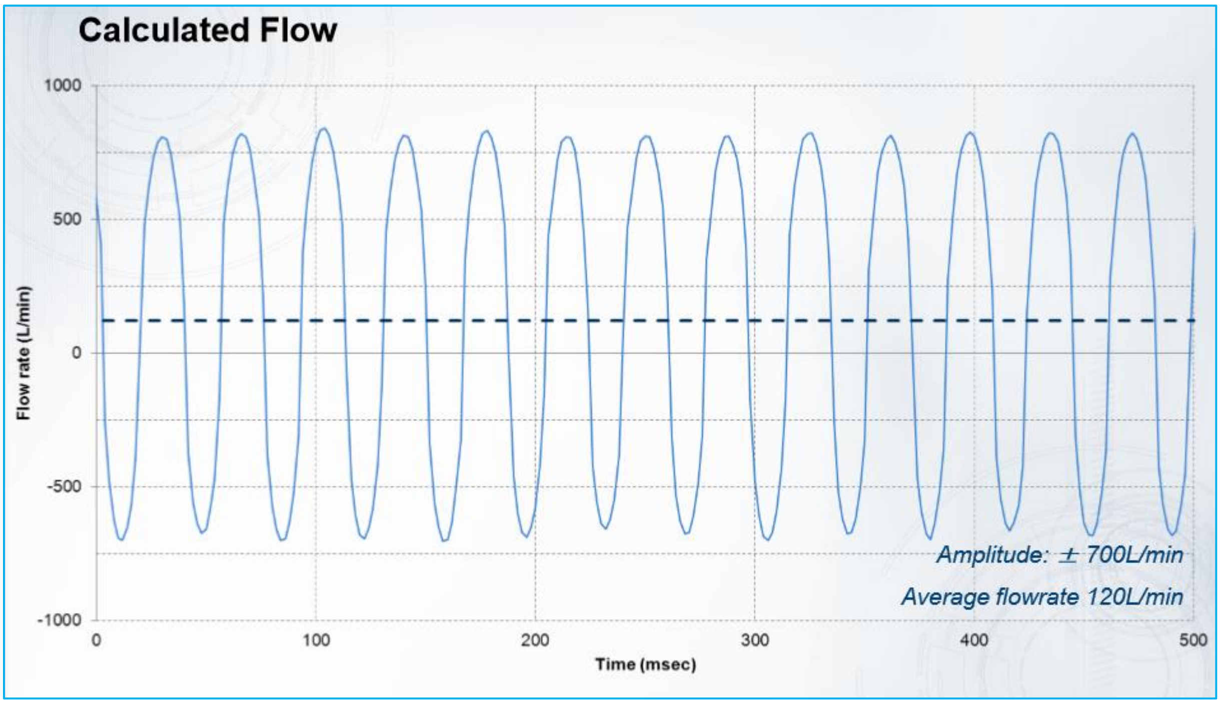
Figure 54. Average flow reading error (1).



Source: Horiba, 2013

In this specific case, we detect a signal with an amplitude of +/- 700 litre/min and an average flow rate of 120 litre/min.

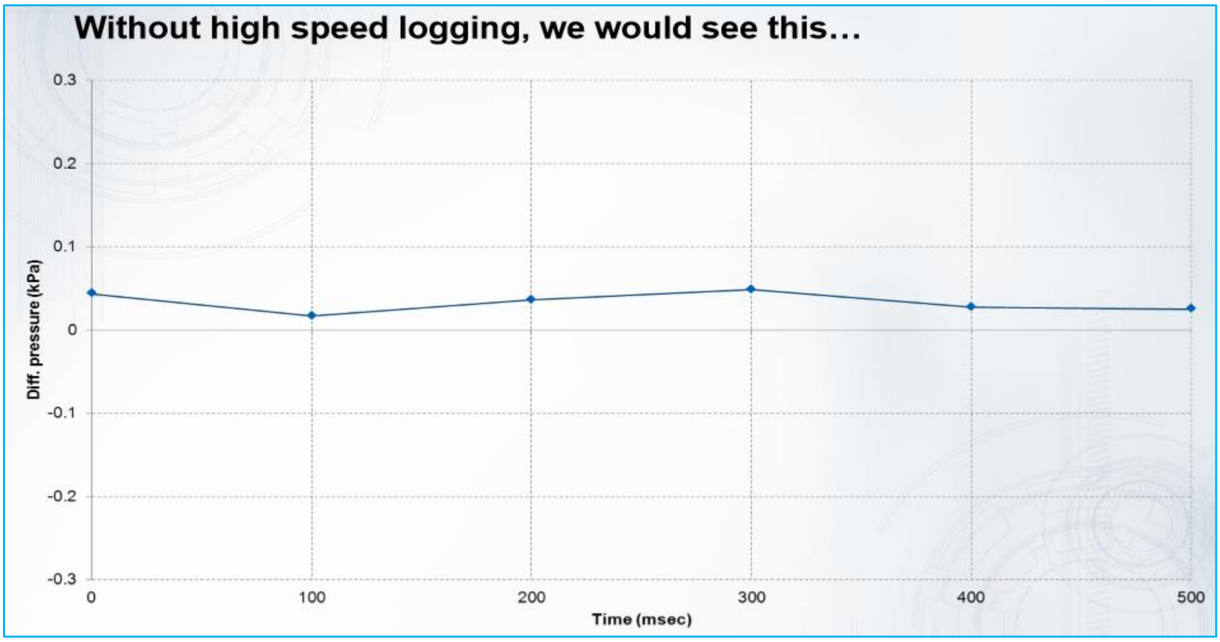
Figure 55. Average flow reading error (2).



Source: Horiba, 2013

Without a high speed logging, the result signal is far from the reality.

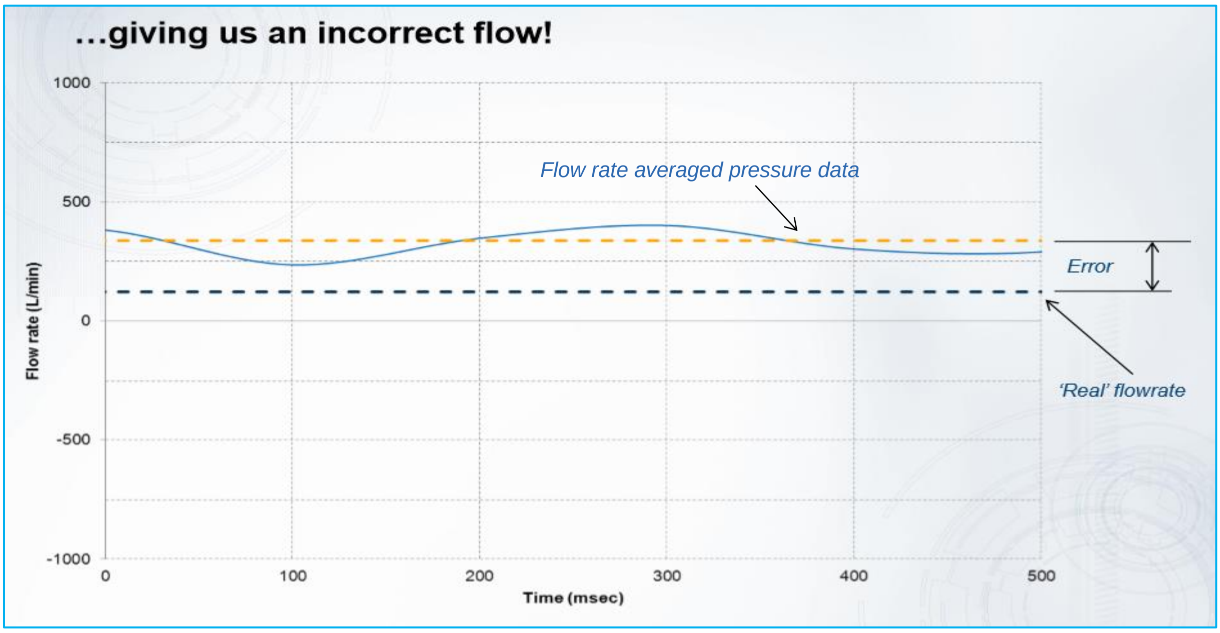
Figure 56. Average flow reading error (3).



Source: Horiba, 2013

that means an incorrect flow reading, as shown in the Figure 57.

Figure 57. Average flow reading error (4).



Source: Horiba, 2013

The error proposed in this study case, is a coarse error.

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